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AN INVESTIGATION OF HEADLIGHT GLARE AS RELATED TO LATERAL SEPARATION OF VEHICLES

by

L. A. Webster

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ABSTRACT

THE HEADLIGHT GLARE PROJECT WAS INITIATED IN THE FALL OF 1964 TO STUDY THE TOLERABLE LEVELS OF HEADLIGHT GLARE AS RELATED TO MEDIAN PERFORMANCE. THIS REPORT, WHICH COVERS THE WORK OF THE PROJECT, BEGINS (PART I) WITH A DISCUSSION OF THE CURRENT STATUS OF KNOWLEDGE ON HEADLIGHT GLARE. THE FACTORS INFLUENCING THE AMOUNT AND EFFECTS OF GLARE, THE SUGGESTED METHODS OF ALLEVIATING GLARE, AND THE SOURCES OF EXPERIMENTAL ERROR ARE INCLUDED.

ACTUAL FIELD TESTING WAS CONDUCTED IN TWO PHASES: (1) DISABILITY GLARE, WHICH AFFECTS SEEING DISTANCE AND (2) DISCOMFORT GLARE, WHICH IS A PSYCHOLOGICAL PHENOMENON. THE DISABILITY GLARE TESTS (DISCUSSED IN PART II OF THIS REPORT) INVOLVED OBTAINING SEEING DISTANCES FOR TEN SUBJECTS, EIGHT TARGETS, TWO BEAM CONFIGURATIONS, AND FOUR LATERAL SEPARATIONS (6, 33, 72, 94 FT). DATA WERE ALSO COLLECTED FOR POLARIZED HEADLIGHTING AT THE 6-FT LATERAL SEPARATION. CONCLUSIONS AS TO THE OPTIMUM LATERAL SEPARATION FOR PROVIDING SEEING DISTANCES EQUAL TO OR IN EXCESS OF THE SAFE STOPPING SIGHT DISTANCE FOR 70 MPH ARE MADE, AS WELL AS STATEMENTS SHOWING THE ADVANTAGES OF POLARIZED HEADLIGHTING FOR THE 6-FT LATERAL SEPARATION.

STATIC AND DYNAMIC TESTS WERE CONDUCTED ON DISCOMFORT GLARE. THE STATIC TESTS (DISCUSSED IN PART III OF THIS REPORT) PRODUCED BCD (BORDERLINE BETWEEN COMFORT AND DISCOMFORT) VALUES FOR TEN SUBJECTS, EIGHT LONGITUDINAL DISTANCES, TWO BEAM CONFIGURATIONS AND FOUR LATERAL SEPARATIONS (6, 33, 60, 94 FT). CONCLUSIONS WERE DRAWN REGARDING THE LATERAL SEPARATION NEEDED TO REDUCE THE DISCOMFORT OF ONCOMING HEADLIGHT GLARE.

THIS REPORT CONCLUDES (PART IV) WITH SPECIFIC STATEMENTS REGARDING THE LATERAL SEPARATION WHICH PRODUCED TOLERABLE LEVELS OF DISABILITY AND DISCOMFORT GLARE. ALSO INCLUDED ARE DISCUSSIONS WHICH EVALUATE THE RESEARCH AND SUGGEST THE DIRECTION OF FUTURE STUDY.

ACKNOWLEDGMENTS

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The work was conducted under the general administrative supervision of Ellis Danner, Program Director, University of Illinois. The specific phases of the work concerned with the preparation of the annotated bibliography and current status of knowledge, the design and conduct of the disability glare field tests, and the design of the discomfort field tests were conducted under the supervision of Ronald R. Knox, project Supervisor, and Robert A. Longfield, Project Investigator. The specific phases of the work concerned with the conduct of the discomfort field tests, the analysis of disability and discomfort glare field data, and the preparation of the project reports were conducted under the supervision of Robert H. Wortman, Project Supervisor, and Lee A. Webster, Project Investigator.

The project Advisory Committee members were Garth J. Thomas and Harry L. Jacobs of the University of Illinois, John E. Burke, James R. Metz, and George E. Moberly of the Illinois Division of Highways, and James L. Wenning of the Bureau of Public Roads.

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EXPLANATION OF TERMS AND ABBREVIATIONS*

c = CANDLE, an older unit of luminous intensity. Based on the "international candle" maintained by a group of carbon-filament vacuum lamps, and used from 1909-1948.

cd = CANDELA, a newer unit of luminous intensity. The primary standard of light is a blackbody radiator operated at the temperature of solidification of platinum. The candle is one-sixtieth of the luminous intensity of one square centimeter of such a radiator. One candle equals one lumen per unit solid angle (steradian) c = 1 lm/ster. (Accepted as the standard in 1948. In the U.S., the use of the term "candle" is being continued.)

cp = CANDLEPOWER, luminous intensity expressed in candles.

fc = FOOTCANDLE, the unit of illumination (density of luminous flux incident on a surface) when the foot is the unit of length. It is also the illumination on a surface one square foot in area on which is uniformly distributed a flux of one lumen. One footcandle equals one lumen per square foot. $1 fc = 1 \, lm/ft^2$.

fl = FOOTLAMERT, a unit or photometric brightness (luminance) equal to $1/\pi$ candle per square foot $1 fl = \frac{1}{\pi} \, c/ft^2$. A theoretical perfectly diffusing surface emitting or reflecting flux at the rate of one lumen per square foot would have a photometric brightness of one footlambert in all directions.

lm = LUMEN, the unit of luminous flux (the time rate of flow of light-luminous energy). It is equal to the flux emitted through a unit solid angle (one steradian) from a uniform point source of one candle.

lx = LUX, the unit of illumination when the meter is the unit of length. $1 \, lx = 1$ m-c or $1 \, lm/m^2$.

ster = STERADIAN, a unit of measure of solid angles. It is the solid angle subtended at the center of the sphere by a portion of the surface whose area is equal to the square of the radius of the sphere.**

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*_IES Lighting Handbook,_ 3rd ed., Illuminating Engineering Society, New York, 1959.

**_Websters New International Dictionary,_ Second Edition, G & C Merriam Company, 1934.

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PART I
CURRENT STATUS OF KNOWLEDGE

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I. INTRODUCTION

Night driving has proven to be much more hazardous than daytime driving. According to recently compiled accident statistics, the night accident rate is generally twice that of day rates.* Visibility is, of course, reduced at night, and other factors such as headlight glare, fatigue effects, and greater possibility of drinking drivers contribute to the higher accident rate. Some of these factors cannot be modified through geometric design and therefore must be approached through the driver education and control or vehicle design. However, the problem of headlight glare and its adverse effects is one which may be successfully attacked directly from the standpoint of geometric design. The effects of headlight glare include temporary loss of vision during and after exposure to glare, fatigue effects, reduced night vision sensitivity caused by the cumulative effect of repeated light "shocks," and general annoyance and discomfort caused by headlight glare.

Glare may be regarded as a sensation experienced when the field of vision contains a light source which has a much higher intensity than the surrounding area. Objects which reflect less light than the glare source then become impossible or nearly impossible to see. Two concepts of glare are defined in the current literature, disability glare and discomfort glare. The former, also termed physiological glare, causes a measurable modification in the visual functions of the driver as a direct result of one or more luminous sources being present in the visual field.(116)** Discomfort glare, also termed psychological glare, is defined as glare which causes discomfort while not necessarily hindering the vision of objects appearing in the visual field.(286) Thus, disability glare is primarily responsible for impairing the ability to perform a visual task, while discomfort glare influences the ease with which the individual can see.(101)

The major objective of this study was to establish the levels of headlight glare believed to be tolerable to the driver of a motor vehicle and to relate these levels to median performance. As discussed above, glare levels are variable and are a function of the glare situation, i.e., disability or discomfort glare conditions. Therefore, their determination should be a prerequisite to any future studies concerning median design features aimed at reducing glare by widening or other glare reducing modifications.

A careful study of the current literature on headlight glare indicated that the phenomena of headlight glare could be subdivided

*Accident Facts, 1965, National Safety Council, p. 47.

**Superscript numbers in parentheses refer to listings in the References.

into two major groups of factors: those influencing the amount of glare, i.e., the amount of light reaching the driver's eyes, and those influencing the effects of glare, i.e., the ability of the driver to see an object. More specifically the factors influencing the amount of glare include:

(1) The headlight system -- specifically the output intensity of the oncoming headlights, the glare intensity of the opposing headlamps, and the headlight configuration.

(2) The roadway factors -- namely the pavement reflectance characteristics, the median width, and the highway's geometric design.

(3) The transmission media through which the light must pass -- specifically the atmosphere and the vehicle's windshield.

The factors influencing the effects of glare include:

(1) The human variables -- such as the driver's age, visual ability, and state of fatigue.

(2) The target factors -- such as the size and shape, the contrast ratio or reflectance factors, and the target's transverse and longitudinal position on the roadway.

The following chapters discuss the findings of past research regarding the above factors. There is also a discussion of the suggested methods of alleviating glare (polarized lighting, street lighting, median barriers, median width, and windshields) and the major sources of experimental error.

II. FACTORS INFLUENCING THE AMOUNT OF GLARE

A. HEADLIGHT SYSTEMS

The automobile headlight is the most important factor in determining the amount of light reaching the eye of a driver. The beam pattern and intensity, the degree of lamp misaim and deterioration, the type of lighting system, and the beam configuration (high or low) are important headlight variables that influence the seeing distance of the vehicle operator during the meeting situation. To determine the degree of safety existing during this situation, these factors have to be quantified in terms of a tolerable level of headlight glare.

1. Output Intensity

As stated by G. W. Onksen,[203] A. J. Harris,[110] and others,[41,191,197] the major problem in headlight design is to provide the driver enough light for adequate visibility while at the same time to minimize the amount of light causing objectionable glare to the opposing drivers. It is obvious that the two design requirements conflict; for to provide necessary light to illuminate objects on or immediately adjacent to the pavement at a safe distance ahead of the vehicle, the light will be too bright for approaching drivers. Consequently, the design of the headlight must be a compromise between these two requirements.

In designing a headlamp to satisfy these two conflicting requirements, R. L. Moore[194] stated that two schools of thought exist, namely the Anglo-American and the Continental European. The former designs the meeting beam to provide the maximum possible seeing distance while recognizing the need to reduce glare as much as possible; whereas, the latter school designs the meeting beam with a minimum amount of glare, while attempting to provide an adequate seeing distance.[54,194]

In the United States, the introduction of sealed-beam headlights in 1939 proved beneficial by standardizing headlights on all motor vehicles manufactured in this country and thereby simplifying service requirements and enforcement problems.[191,203] As vehicle registrations and miles traveled increased, the average driver had less opportunity to use the high-beam headlamps, therefore, it was mandatory that headlighting researchers devote attention to improving the seeing distance obtainable with the low-beam. This research resulted in an improved version of the sealed beam lamp which was first introduced in 1955 and which provided an increase in seeing distance of 50 to 80 ft in low-beam seeing distance for a total of about 375 ft, and gave improved visibility under adverse weather conditions.[41,197,236] This improvement was accomplished by: (1) raising the top, right side of the lower beams by 1/2 degree, (2) placing a shield in front of the lower beam filament to eliminate the above horizontal direct filament light, and (3) increasing the low beam power from 35 to 40 watts and the upper beam from 45 to 50 watts.[197,203] However, since one headlamp housed both beams, the lower beam filament was placed "off focus," thereby creating still another compromise.[41,191,203]

As a result of dissatisfaction with the necessity of compromises in the 1955 headlamp improvement, the Vehicle Lighting Committee of the Automobile Manufacturers Association and the Lamp Manufacturers Committee prepared a list of technical guidelines to govern the development and improvements of future headlamps.[41] In 1957, a four-headlamp or dual headlight system was introduced which satisfied the technical requirements. This system solved the problem of compromising filament location within the single lamp by providing separate lamps for each beam and thereby permitting the optical design of each beam to be optimized.[41,161,191,203] The low beam power in this system was increased to 50 watts and the filament was placed "on focus," thus allowing greater control of the light along the right side of the beam.[42] Consequently, this system offered a more efficient optical control by allowing each lens to be designed for specific beam pattern requirements and through optimum filament placement at the focal point, an increased lower beam seeing distance, and an improved upper beam as a result of the wattage increase.[203] With the adoption of the dual headlight system, the low beam seeing distance was increased to about 450 ft, with properly aimed lamps, without increasing the glare for opposing drivers.[41,236]

A more recent improvement in 1959 was in the lower beam of the single, sealed beam system to make its performance comparable with the dual headlight system.[161] The improvement was accomplished by placing the lower beam filament at the focal point of the reflector with no change in bulb wattage. The upper beam, however, does not have equal performance to that of the dual headlight system since the generators on older model cars could not supply the power required for the necessary wattage increase.[161]

Many tests to determine the optimum beam design are mentioned in the literature (see References 13,53,54,96,108,109,110,154). The most acceptable optical system consists of a parabolic reflector containing a small light source, with the light being distributed by a lens.[191,194] Other factors, such as efficient use of the generated light, the tolerances permitted in manufacturing the reflector, the accuracy of the source focus, the efficient distribution of the light forming the beam pattern, and the light source dimensions, enter into designing the beam for adequate seeing distance.[191]

Published research on headlight beam design has concentrated primarily on determining, through field tests, the type of beam pattern which will provide the greatest seeing distance. The studies have been concerned with the car-meeting situation in which the test subject must detect a given target at a specific position in the visual field under conditions of glare from opposing high or low headlight beams. Various experiments performed under these conditions, using stationary and/or moving vehicles, have indicated the distribution of light in the beam pattern which is preferred with the current type of headlighting system.

One such test, reported by J. B. DeBoer and D. Vermeulen[53,54] in 1951, compared the American sealed beam lamp with a typical Continental European lamp. The sealed beam lamp tested had an asymmetrical lower beam which distributed more light in the right-hand side of the beam pattern and possessed a gradual cutoff near the horizon. The upper, or driving beam, of the lamp had a wide horizontal spread of light and gradual cutoff above the horizon in the vertical direction.

The European beam had a more restricted horizontal and vertical spread of light in the upper beam and a sharper horizontal and vertical cutoff in the lower or passing beam.

In terms of the intensities permitted in the center of the beam, the two lamps tested were essentially identical for the passing beams. Thus, the major differences between the headlamps tested consisted of (1) the greater above horizontal intensities of the sealed beam, (2) the asymmetrical light distribution of the sealed beam's passing beam, (3) the higher center intensities in the upper beam of the European lamp, and (4) the wider horizontal spread of light in both beams of the American lamp. To compare the seeing distances obtained with each of these lamps, the authors used targets which would be small enough to reduce the influence of silhouette seeing because small targets represent a major hazard to high speed travel and because silhouette seeing can yield distance values which are too liberal for traffic safety standards. Consequently, this study indicated that targets used in seeing distance tests should not exceed 40 cm (approximately 16 in.) in height, although heights both above and below this value were used in these tests.

By using both a stationary glare source and two stationary observers, who rated the target visibility on a five point scale ranging from "not visible" to "strikingly visible," the seeing distance values were obtained for the various combinations of headlamp type, beam condition, target size, and target placement. The comparison between the American sealed beam headlamp and the European headlamp indicated that the upper beam of the European lamp yielded seeing distances which average 15 per cent greater than the sealed beam lamp under no-glare conditions. If the two vehicles were located 200 m apart longitudinally in the meeting situation, the passing or lower beam of both lamp types provided a greater seeing distance. The comparison of the passing beams indicated that only small differences between the two existed, with the better performing lamp being dependent upon the vertical aim of the headlamp and the transverse position of the target on the roadway. The authors concluded, however, that for target heights less than or equal to 40 cm, the passing beam of the European headlamp produced slightly greater seeing distances.

In 1954 G. Grime[96] and A. J. Harris[108,109,110] published papers dealing, in part, with the horizontal cutoff of the beam pattern and the lamp type in terms of their influence upon night seeing distances during the meeting situation. The lamp types, including the old and new British lamps and two European lamps, were compared in moving vehicles tests in which the subjects indicated the headlamp they preferred and the degree of glare encountered. The European headlamps had high-intensity narrow beams, whereas the other tested were either wide, low-intensity beams, or wide beams with a more gradual side cutoff than the European, or beams possessing a sharp side cutoff which primarily illuminated the nearside pavement edge. Some conclusions of tests with these passing beams included (1) a desire for good illumination of the nearside edge of the traveled lane, (2) an increase in glare on wet pavements as compared to a dry road surface, and (3) the glare on wet surfaces resulting from a wide uniform beam pattern, was considered objectional, but on a dry road there was no glare.[96,110] The headlamp found to be most satisfactory was the new British type in which the light was focused downward and toward the nearside of the pavement. However, a European lamp having a wide spread and a lower maximum intensity was considered almost equivalent to the British beam when adjusted to deflect to the side. Consequently, the authors concluded that if a beam is adopted for uniform use, it should possess a light distribution similar to the British beam or be a "radical departure from all conventional types."

In addition, A. J. Harris[108,110] concluded that increasing the sharpness of the side cutoff of the beam will increase the seeing distances; however, the increase may apply only to nearside objects with little or a negative improvement for offside objects. Moreover, if side cutoff is designed into the meeting beam pattern, it should not extend much below the horizontal in order to maintain the visibility of objects located near the offside pavement edge.

G. E. Meese,[191] in his discussion of the American sealed beam headlamp, stated that since the light generated is limited by the power available, the brightest portion of the beam pattern is focused straight ahead with a horizontal spread of 8 degrees and a vertical dispersion of 3 degrees. However, since few sections of highway are continuously straight and of constant grade, a horizontal spread of 40 degrees is given at lower intensity illumination in the top and bottom of the beam pattern in order to provide light on hills and to illuminate the pavement immediately in front of the vehicle. Moreover, he stated that the best current passing beam has a non-symmetrical beam pattern.

G. W. Onksen[203] related in his paper on the American quadralamp, i.e., the dual sealed beam system, that the high beam should provide the high intensity light required for seeing distance to exceed safe stopping distance, for adequate visibility of the full road width, and for sufficient illumination up hills, in dips, and around curves. This light, however, will be too bright for the meeting situation; thus, the low beam is needed for passing opposing vehicles, for providing adequate visibility in inclement weather, and for enhancing silhouette seeing. To satisfy these passing beam requirements, the American headlight industry has formulated rules which prevent the use of asymmetric-right flutes in the lenses of the sealed beam to help eliminate the possibility of stray light being bent to the left and into the eyes of an opposing driver. Consequently, to focus the high intensity portion of the beam on the right side of the road without using asymmetric-right flutes, the axis of the lamp reflector is turned to the right. By tilting the reflector axis downward, the light from the lens prisms, which control the pattern's vertical spread, is kept below the horizontal, thereby reducing another source of glare.

Papers published in 1963 by G. Johansson, et al.,[154] and S. Bergstrom[13] discussed a recent series of tests comparing seeing distances obtained with high-beam headlights, low-beam symmetrical headlights, and low-beam asymmetrical headlights. A comparison between high-beam headlights and low-beam symmetrical headlights showed that the high-beam lights provided seeing distances equal to or greater than the dipped beam during the entire meeting situation. This conclusion was confirmed by tests using targets of four different reflectances. Tests comparing the two passing beams from symmetrical and asymmetrical headlights showed that asymmetrical headlights on both the approach car and the experimental car resulted in much longer seeing distances than with any other combination. A final comparison of high-beam headlights with asymmetrical low-beam headlights showed that high-beam lights provided much longer seeing distances throughout the meeting situation. Thus, the authors concluded that the increase in visual comfort obtained by dipping the headlights during the meeting maneuver was accompanied by a loss of seeing distance through most of the meeting situation.

In addition to determination of the desired type of headlight beam pattern and the most desirable optical components of the lamp, the selected headlamp must satisfy the primary design requirements of providing maximum seeing distance with minimum disability and discomfort glare. Consequently, the distribution of luminous intensity in the beam pattern must be carefully determined in order to establish the probable seeing distance and glaring intensity and to satisfy the applicable statutory limitations.(53,203)

Other studies dealing with the problem of determining seeing distance under various conditions of glare, highway geometrics, object type and position on the roadway, and visual ability of the driver are listed as References 25,29,53,74,95,96,108,109,110, 141,147,154,233,238,239, and 240. In two early studies, an attempt was made to determine the relationship between seeing distance and beam intensity. V. J. Roper and E. A. Howard(238) used a target which simulated a pedestrian dressed in dark clothing and a constant vehicular speed of 50 mph, and concluded that the combined luminous intensity from both beams had to be approximately 75,000 candlepower if seeing distance was to exceed the safe stopping distance for the average driver, vehicle, and road condition, with no opposing glare. The safe stopping distance was exceeded by only about 5 ft for this beam intensity and by about 25 ft for an intensity of 100,000 cp (candlepower), which exceeds the 75,000 cp statutory limit in the United States. On the other hand, when glare from opposing headlights was present in the visual field the driver's seeing distance was considerably reduced, with the degree of reduction depending in part upon the glaring intensity. This relationship was influenced to only a minor extent by the headlamp intensity illuminating the test obstacle. The test results indicated that with a glare intensity at the driver's eye of 1000 cp, visibility distance was reduced by approximately 1/3 of the no-glare value, while an intensity of 7000 cp reduced visibility by about 2/3 of the no-glare value. These results were based upon the average of eight observers under test conditions in which the opposing headlight intensity was constant throughout the entire meeting situation, and the dummy obstacle was located at the rear and 10 ft to the side of the stationary glare source.

In a paper published in 1948, V. J. Roper(233) summarized several studies which indicated that average upper beams of a sealed beam system produced about 60,000 cp, which was adequate to reveal the above mentioned dummy at a distance of 420 ft for a 50-mph vehicular speed, average driver inattention, and no glare present. However, with a glare source present at a longitudinal distance of 3200 ft and with a 40-mph vehicle speed, the seeing distance was reduced to 300 ft for perfect driver attention, and 210 ft for an average attention factor. With the glare source at a distance of 1200 ft, the glare at the driver's eye became objectionable, i.e., greater than 0.02 fc (footcandle) but less than 0.1 fc which was intolerable, and the seeing distance, using high beams, equaled that obtained using passing beams. For the last 200 ft, the driver's seeing distance dropped to 150 ft which is below safe stopping distance of 165 ft for a speed of 40 mph under average conditions. To improve this situation, V. J. Roper proposed that upper beam candlepower be increased 50 per cent and the glare intensity of the lower beam be reduced 50 per cent. Tests performed using this revised sealed beam indicated that for a vehicular speed of 40 mph, seeing distance exceeded safe stopping distance during the entire meeting situation, even if average driver inattention was considered.

Several studies have been performed which have used essentially the same target, namely a 16-in. square or 16-in.-diameter circle each having a reflection of 7 to 9 per cent. (See References 53,108,109,110,141,147,239, 240,286.) J. B. DeBoer and D. Vermeulen[53] reported that to see an obstacle when the contrast between it and the pavement was unfavorable, required approximately 5 lux on the obstacle. Thus, to provide this illumination at a 100-m distance, each lamp had to have a luminous intensity of 25,000 cd (candela) in the axial direction. The intensities of beam patterns of the upper beam in the axial direction of a typical European and American lamp were found to be 60,000 cd and 30,000 cd, respectively. Using these same lamps, seeing distances of 80 m were measured for the sealed beam lamp and 100 m for the European lamp under high beam conditions. Their work with the lower beam of these two lamps in a meeting situation indicated that for a longitudinal vehicle separation of 100 m, the vertical illumination of an object in the center of the driving lane and the glare from oncoming vehicles were about four times greater with the sealed beam. At 50 m the glare from the American lamp was three times greater, while the illumination was only 1.33 times greater than the European lamp. V. J. Roper and G. E. Meese[239] reported that the present (1952) headlighting system could not provide a seeing distance in excess of safe stopping distance for the entire meeting situation. Moreover, their work and that of D. M. Finch[64] indicated that clear road seeing distance was reduced by 20 per cent when the illumination at the driver's eye reached a value of 0.002 fc and by 50 per cent with 0.04 fc illumination. However, D. M. Finch found that glare was not objectionable until the illumination at the driver's eye reached about 0.02 fc, which according to G. E. Meese would cause a reduction of about 43 per cent in the open road seeing distance.

A. J. Harris[108,109,110] has studied the relations among beam intensity, the ratio of glaring intensity to illuminating intensity, and seeing distances. His experimental results indicated that, over most of the range tested, glaring intensity was linearly related to seeing distance regardless of the illuminating intensity. Thus glare had a greater influence when illuminating intensities were low. His results showed that seeing distance, for a glaring intensity greater than 500 cd, was dependent more upon the ratio of illuminating to glaring intensity. For example, if a value of 1000-cd glare is assumed a tolerable value, as other tests have indicated, and the illuminating intensity is taken as 10,000 cd, i.e., the maximum value permitted by SAE specifications at the point 0.5 degrees down, 2 degrees right, then the minimum seeing distance will be about 185 ft or slightly more than that required to stop from a speed of 40 mph.[110]

V. J. Jehu[141,147] using a computational procedure developed by the Road Research Laboratory, increased this estimate of minimum seeing distance to about 206 ft and 219 ft for the American and British quadralamp systems, respectively. He also stated that the maximum allowable glaring intensity should be in the range of 900 to 1800 cd. Using this range and the above mentioned illuminating intensity at 0.5 degrees down, 2 degrees right, the data collected by A. J. Harris[110] indicated seeing distances of about 160 ft and 190 ft for 1800 cd and 900 cd glare, respectively.

2. Glare Intensity

Two recent papers deal with the relation between glaring intensity, illuminating intensity, and seeing distance. The results of tests performed by V. J. Roper and G. E. Meese[240] indicated that as the beam intensity increased from 6000 cp at a point 0.5 degrees down and 2 degrees right, to 20,000 cp, the minimum seeing distance increased from roughly 260 ft to 360 ft for the low beam meeting situation with no attention factor applied. A somewhat smaller increase was found when the roadway geometry included horizontal curvature.

R. Zechnall[286] presented a comprehensive discussion of seeing distance and glare and stated that the specified European glaring intensity was 400 cd for light falling above the horizontal and 200 cd at 2 degrees to the left of the lamp center. Moreover, maximum seeing distances obtainable using the lower beam ranged between 80 and 100 m. Tests were performed to determine if disability glare, i.e., glare which reduces seeing distance without necessarily creating discomfort, could be overcome by increasing the illumination of the roadway. Using proportional illumination levels which increased by a factor of 1.7, from 1 to 5, thereby increasing the illuminating intensity at all points in the beam pattern, minimum seeing distance was found to increase from 50 m to 60 m for nearside objects and from 30 m to about 44 m for offside objects. The author attributed this increase in seeing distance to an increase in both contrast sensitivity and adaptation level. Thus, if contrast sensitivity improves, increases in beam intensity will provide greater seeing distances even though glare is also increased.

Several facts regarding the phenomenon of discomfort glare were also presented by R. Zechnall. In part, these included (1) discomfort glare is dependent upon the light source luminance, (2) discomfort occurs at a specific ratio of source luminance to surround luminance, and (3) the angle between the source and the driver's line-of-sight influences discomfort. Thus luminance creates discomfort. The author stated that the lowest luminance of the surrounding area controls the highest permissible luminance, i.e., the level considered to be tolerable. In addition, headlamps having greater lens surfaces should be used, since the smaller surfaces have higher luminance. Thus, with the current "E-type" headlamp, a luminance of 6cd/cm^2 (candela per sq. cm) at the intersection of the roadway horizon and the vehicle center (extended to the horizon) is permissible.

Misaim and Deterioration

In designing a beam pattern for use under present night driving conditions, the operating conditions of the headlight aim and the deterioration of beam intensity must be considered. Because any present lighting system used is subject to the operating and maintenance practices of the driving public, the degree of misaim found to exist with current vehicle use is of major importance in selecting the standard of aiming required for efficient operation of the lighting system. To determine the extent of headlamp misaim common to current lamp use, several studies have been conducted in which this source of headlight glare was closely examined.[95,134,136] In an early study performed in Great Britain, the survey results indicated that on main highways near London the problem of glare was not generally caused by drivers who failed to depress their headlights for approaching vehicles.[134] A primary cause of glare was headlight misaim with approximately 25 per cent of the vehicles on unlighted highways and 10 per cent of the vehicles on lighted highways causing glare, while only 5 per cent and 2 per cent, respectively, failed to dim their headlights. For these same vehicles and highways, the extent of misaim was indicated by the fact that 17 per cent of those vehicles using the passing (low) beam were found to create glare.

Another British study performed by V. J. Jehu[136] in 1952 determined the degree of misaim and the maximum lamp intensity of headlamps on 400 passenger cars and 400 commercial vehicles. Since no regulations specifying the dip or deflection of headlamps exist in Great Britain, the "correct" aim was taken as straight ahead with a dip of 0.5 degrees for the driving (upper) beam and 3 degrees for the meeting (lower) beam. Considerable variation was found in both the vertical and horizontal aim of the headlamps, with the mean vertical aim being about 0.7 degrees down for the driving beams and 1.1 degrees down for the meeting beams of all passenger cars tested. The mean horizontal aim of the passenger car lamps was 0 degrees, i.e., straight ahead, for the upper beam, while for the lower beam the mean value was 1.5 degrees left, i.e., toward the nearside edge of the pavement. About 30 per cent of the cars and 20 per cent of the commercial vehicles had beams aimed within ±0.5 degrees of "correct" aim in either the horizontal or vertical planes, but only 9 per cent and 5 per cent of the lamps, respectively, met this standard in both directions. No estimate of aim was made on 13 per cent of the driving beams because of deterioration or defocusing, and 6 per cent of the lamps were not operative. Considerable lamp deterioration was evident; about 10 per cent of the meeting beams had a maximum intensity less than 1000 cd and 40 per cent of the driving beams were less than 5000 cd in maximum intensity. Consequently, the authors believed the current (1952) standard of headlight aiming to be very poor.

During the summer of 1952, G. Grime[95] conducted a study of the glaring intensity of low beam headlamps at sites in Texas, Maryland, New Jersey, and Washington, D.C. In addition, measurements of the maximum lamp intensity of the upper beams were recorded in Washington, D.C., and a count of the willingness of drivers to depress their headlights when approaching an opposing vehicle was made on rural roads in Texas. The survey results showed a high degree of correct aiming with 60 to 70 per cent of all the glaring intensities between 400 to 800 cd. Moreover, the results indicated that the standard of aiming was better in New Jersey and Washington, D.C., which have vehicle inspection programs, because significantly lower numbers of vehicles had glare intensities over 800 cd. Thus, although the average glare intensity was low, indicating good aim, many very poorly aimed headlamps were encountered, e.g., 10 per cent of the lamps in Washington, D.C., and 25 per cent in Maryland had a glare intensity greater than 1000 cd.

Deterioration measurements indicated a maximum intensity of both high beam lamps to be about 20,000 cd for about 55 per cent of the vehicles compared to the design candlepower of 64,000 at 6.4 volts. The author concluded that about 25 per cent of the drivers may have seeing distances less than two-thirds of that possible with perfect aiming and the design intensity, i.e., 152 ft. The author also found that 20 to 25 per cent of all drivers in a meeting situation on rural roads in Texas refused to depress their headlights to the lower beam. Thus the glare problem in the United States may be more a result of improper beam usage than from headlamp misaim.

It is important that the influence of misaim and lamp deterioration on seeing distance be known if for no other reason than to convince the public and vehicle maintenance personnel of the benefits to be derived by adhering to the aiming and intensity specifications. In this regard, several studies have been made which better enable the headlamp industry to evaluate modifications in the present lighting system.[108,109,110,236,240,286] In a study performed in Germany, R. Zechnall[290] showed that approximately 5 per cent of the headlamps tested caused glare because the vertical cutoff was aimed too high. To test the possibility of providing the driver with a lever by which he could adjust the vertical aim of his headlamps while driving, experiments were conducted using experienced headlight research technicians as drivers. It proved to be virtually impossible to properly aim the beam without a specialized aiming device, because nearly all the technicians set the beam too high.[286]

V. J. Roper[236] has determined the magnitude of the loss in seeing distance for a misaim of 0.5 and 1.0 degree (low) at the point 300 ft ahead on the right-hand pavement edge, i.e., the point in the beam pattern at 1/2 degree down, 2 degrees right. For the specific conditions of no glare, 7 per cent object reflectance, 50-mph vehicle speed, low beams, and perfect driver attention, the 1940 sealed beam provided approximate seeing distance of 240 ft with correct aim, 150 ft with the lamp aimed 1/2 degree low, and 90 ft at 1 degree low. The 1955 improved sealed beam provided about 375 ft with correct aim, 240 ft at 1/2 degree low, and 110 ft at 1 degree low, and the 1957 quadralamp system provided 450 ft, 330 ft, and 280 ft, respectively. Thus the author stated that under more adverse conditions including driver fatigue, the visibility situation may be very hazardous. Moreover, the author believed the average misaim to be about 1/2 degree, or more, based on experience.

In the previously discussed study, V. J. Roper and G. E. Meese[240] explored the effect on seeing distance of having a misaimed beam with 20,000 cp at a point of 0.5 degrees down, 2 degrees right. By permitting this misaim lamp to oppose a car with 8000 cp (the average of the maximum and minimum SAE specifications at this point) the seeing distances of the two drivers were obtained. The minimum seeing distance value with the misaimed lamps was about 420 ft. However, for the driver of the vehicle having the correctly-adjusted, average-intensity lamp it was approximately 200 ft, as opposed to 230 ft when he was facing lamps identical to his own. Thus operators of older cars will experience a reduction in seeing distance if they face an increased intensity lamp which is misaimed high and to the left.

A. J. Harris[108,109,110] and V. J. Jehu[135] presented a thorough discussion of both the prevailing state of lamp misaim and deterioration found in Great Britain and the effect of these two factors on beam design as well as minimum seeing distance. Using charts prepared for an assumed beam pattern and the seeing distance versus beam intensity figures mentioned earlier in this section, the probabilities of the glaring and illuminating intensities equaling any chosen value can be determined if the beam design and aiming standard are known. Therefore, by selecting various aiming and deterioration levels, the probability of the minimum seeing distance being less than an arbitrary distance (d) was calculated. The results indicated that if a seeing distance less than 150 ft was to occur in no more than 10 per cent of the vehicle encounters, using the new (1952) British lamps, the standard deviation for vertical aim must range between 0.25 to 0.5 degrees while the sharpness of the cutoff varies from about 3 to 5 degrees, respectively. Hence, for this example, the aiming and beam cutoff standards are extremely rigid and become almost impossible to meet for a seeing distance of 200 ft. Moreover, if the lamp intensities have deteriorated to 1/4 of their original value, the 150-ft seeing distance situation becomes virtually impossible.(110)

The author also discussed the effect of misaim on the glaring intensity and concluded that misaim will influence discomfort more through its effect on the glaring intensity than its effect on the background luminance. By the above mentioned method, the author suggested that improvements in minimum seeing distance would not produce increasingly greater discomfort and glaring intensity, since the intensity exceeded in a given percentage of vehicle encounters decreased as seeing distance increased. Thus improvements in the standards of aiming and sharpness of cutoff limited probably by intermittent glare caused by the pitching motion of the vehicle, will improve glaring intensities, if seeing distance is improved.

A recent study by K. Rumar(244) focused on the visible distance of a 6 per cent reflectance target placed beside or 40 m in front of the glare source. The visible distance was not significantly increased by downward misalignment but with an upward misalignment of 1 to 2 degrees it decreased about 25 per cent.

<u>Configuration</u>

V. J. Jehu(139,145) conducted studies in which the accuracy of measuring both vertical and horizontal aim was determined for several categories and makes of headlamp inspection equipment, including American, British, and continental European equipment. In summary, the conclusions were that vertical aim, which was measured in relation to the surface the vehicle rested upon could generally be determined with ±0.2 degrees, and that horizontal aim, which was related to outstanding vehicle characteristics, could be established within ±0.5 degrees if favorable conditions exist.(145)

In the United States, this problem is not as acute, because every headlamp is equipped with three aiming pads which are positioned on the lamp face during the manufacturing process such that the lamp is properly aimed when the plane established by these pads is normal to the vehicles longitudinal axis. Thus the aiming process involves only the use of spirit levels and strings or sights, thereby eliminating even the need to light the lamp.(191)

Headlamp mounting height enters indirectly into the problem of beam design, since it appears to influence the seeing distances obtainable with the present headlighting system. In one early British study, the author, in the course of proposing rules for headlamp adjustment, stated that the lamps should be mounted with their centers no higher than 3.5 ft, preferably no lower than 2.5 ft, and never lower than 2 ft above the pavement surface in order to prevent excessive glare to opposing drivers.(134)

In a more recent study, V. J. Roper and G. E. Meese[240] determined the difference in seeing distance between a 26-in. and 31-in. mounting height. For a lamp having an intensity of 10,000 cp at a point 0.5 degrees down and 2 degrees right in the beam pattern, the average driver experienced a loss of 60 ft in seeing distance as the mounting height was lowered from 31 in. to 26 in. Using the same beam mounted at 31 in. and 26 in., road tests with opposing glare present, indicated that the average minimum seeing distance, ignoring driver inattention, were 300 ft and 253 ft, respectively. Thus the loss expected from the theoretical calculations closely agreed with the actual average loss in seeing distance.

B. ROADWAY FACTORS

Of the many roadway factors influencing the amount of glare, pavement reflectance, median width, and highway geometrics appear to be the most important and are discussed in the following sections.

1. Pavement Reflectance Characteristics

With the advent of a nationwide system of freeways and large increases in the national population, it is expected that many people will have occasion to travel the highways after dark. The ease and safety with which this can be accomplished depends to a large extent on having adequate seeing conditions for night driving. One factor which contributes to the night performance of a highway facility is the reflective properties of the pavement surface. The surface may be considered as being composed of small, individual units of reflective surfaces which are oriented according to certain distributive laws.[20] Under normal conditions, automobile driving at night is usually done with an illumination of approximately 3025 degrees Kelvin and with intensities giving an average brightness ranging from 4 to 0.003 foot-lamberts.[224] Within this range of brightness there is a decrease in visual acuity, contrast, form perception, stereoscopic depth perception, the ability to judge size, motion and position, and compensation to visual stimuli. At this level of illumination, form and silhouette vision take the place of acuity and the human eye changes from photopic (cone) to scotopic (rod) vision.

Pavement reflectance varies considerably among pavement types and even among pavements of the same type. J. T. Fitzpatrick[66] used a value of 18 per cent reflectance as a standard of ordinary pavement surfaces in his study with reflectorized roadway treatments. According to C. H. Rex[221] a medium-reflectiveness pavement surface had a reflectance of approximately 10 per cent and a high-reflectiveness pavement had a reflectance of about 20 per cent or more.

D. M. Finch[64] reported that the brightness of a gray concrete road surface varied from 0.082 to 0.011 foot-lamberts with high-beam headlights. The range for low-beams was 0.07 to 0.02 foot-lamberts. O. W. Richards[224] found that brightness on a concrete section of parkway was 0.12 foot-lamberts with high and 0.2 foot-lamberts with low-beam headlights. Brightness values on asphalt were 0.16 and 0.12 foot-lamberts for high and low beams, respectively. C. H. Rex[221] estimated that during dry weather conditions medium-reflectiveness asphalt pavement requires about twice as much light to produce the same pavement brightness as that derived from high-reflectiveness pavement surfaces.

For an illuminated test location, H. R. Blackwell[21] reported an average illumination value of about 2.4 foot-candles for medium-reflectiveness asphalt pavements and approximately 1.2 foot-candles for high-reflectiveness concrete pavement. The suggested minimum pavement brightness value for a lighted highway was about 0.6 foot-lamberts.[220] H. R. Blackwell also ran target tests in conjunction with his study of pavement brightness. Two targets were used in these tests, one, a toy dog having a reflectance below either concrete or asphalt and the second, a mannequin, with a reflectance between that of concrete and asphalt. The dog was easier to see on the concrete because its reflectance was closer to that of the asphalt. Visibility of the mannequin differed little between the concrete and the asphalt pavements since the reflectance differed by about the same amount from each of the two pavements. The test results showed that for both pavements the two targets required an average horizontal illumination of 1.90 foot-candles for adequate visibility at 200 ft ahead in the driving lane. Measurements taken with the targets in the outside lane indicated that illumination should be about 3 times greater than the inside lane at distances of 180 to 200 ft.

The reflectance characteristics of a pavement surface will change appreciably as the surface is polished with wear.[23] Increasing degrees of surface wetness will also have the effect of eliminating the normal surface condition which is made up of many small reflecting surfaces and will give the effect of a relatively smooth reflecting surface. If the highway becomes completely flooded, the brightness pattern of the pavement surface will degenerate into a series of narrow streaks.[147] These characteristics differ from one road surface to another and also very considerably for the same surface from levels of dry to wet.[23] These changes in surface characteristics and the decrease in visibility due to the weather condition causes driving in adverse weather to demand an effort, especially in heavy traffic, which greatly exceeds that required of a driver in good weather.

Highway pavement surfaces in the United States may be wet as much as 15 per cent of the time.[221] With adverse weather conditions such as rain, ice, or snow existing on these pavements at night, visibility can be greatly reduced. C. H. Rex[221] stated that even for dry weather conditions it ook twice as many foot-candles on medium-reflectiveness asphalt pavement to produce a pavement brightness which was equivalent to that produced on a high-reflectiveness pavement surface.

The use of pavement markings is very important in nearly all driving conditions but they are especially important when driving at night and visibility is limited. Several experiments have employed the use of reflectorized paints on sections of exit and entrance ramps at a major interchange area.[66,132] Although these reflectorized treatments were found to not greatly influence the normal nighttime operating characteristics of the interchange, pavement markings do aid the vehicle driver in many ways at night, as well as during the day, without diverting his attention from the roadway. Markings have limitations in that they are not clearly visible under some weather and nighttime driving conditions. Better marking materials have been and are continually being developed which aid in visibility and which are more durable under all driving conditions.

2. Median Width

A considerable number of experiments have been conducted with medians to determine the optimum width for reduction of glare. O. A. Deakin[45] has stated that some type of glare screen should be used with all medians less than 50 ft wide. O. A. Deakin[46] also stated that the use of wider medians would allow natural vegetation to remain in the median during and after highway construction and thereby serve as a glare screen. He advocated 8- to 10-ft medians for multilane highways in urban areas and 60- to 80-ft medians in rural areas to provide both space for plantings to screen headlight glare and for traffic guidance.

As glare is a major factor in median design, research has been conducted relating both these factors to visibility. L. L. Holladay[124] found that the least perceptible brightness difference between an object and its background increases directly with the illumination at the eye from the glare source and varies approximately inversely with the square of the angle which the glare source makes with the line of vision. This law is practically independent of brightness, size, type, distance, etc., of the glare source. As this relation shows, generally known as the Stiles-Holladay Law, and as confirmed by experimental results,[124,141,147] the glare effect caused by a glare source does increase up to a certain point in the meeting situation where the square of the angular separation between the glare source and the line of sight becomes sufficiently large to offset the increase in illumination at the observer's eyes. The glare effect then decreases rapidly as the vehicles complete the meeting and passing maneuver.

The above relation has been of considerable value in investigating the manner in which visibility, using current headlight systems, varies with the lateral separation of opposing headlights on tangent and curved sections of highway. One such experiment by V. J. Jehu and G. Hirst[153] used five lateral separations of the opposing vehicles at 10, 25, 40, 70, and 130 ft. A curved section of 3000-ft radius was also used. Results showed that medians of 10 to 20 ft considerably reduced glare effect from low beams, but a median of 70 ft or more must be used to reduce discomfort glare from high beams to a tolerable level. To reduce the peak angular glare from upper beams to negligible proportions, the median width must be 100 to 120 ft.

An alternative to the very wide median, glare screens in the central reservation[148] can be used. The screen can be constructed such that the cutoff angle of the screen is sufficiently large enough to black out that portion of headlight glare where angular glare from the opposing beams is the most intense.

3. Highway Geometrics

The trend in current highway construction is to utilize medians of various widths to reduce headlight glare, to guide traffic, and to provide a factor of safety from head-on collisions. At night, the changing geometry of a highway can influence the amount of glare to which drivers are exposed. Experiments have shown that on tangent, level grades, or on hills and curves where the headlight beams of one car are thrown directly into the eyes of the driver, or where glare is suddenly flashed into the driver's eyes, high-beam headlights will provide seeing distances which are greater than those provided by low-beam headlights for the entire meeting process.[154] This seemed to hold regardless of the reflectance of the objects viewed.

Experiments conducted by V. J. Roper and G. E. Meese[240] showed that increasing the low-beam candlepower at the standard focus point of 0.5 degrees down and 2 degrees to the right above the present SAE (Society of Automotive Engineers) maximum of 10,000 cp gave longer seeing distances on a straight roadway when approaching, meeting, and proceeding beyond an opposing car with the same beam intensities. Tests on curves using higher candlepower for low beams under meeting conditions also showed an increase in seeing distances when the beams were properly focused. Some relief from glare in a meeting situation can be achieved if the driver's eyes are focused at the right edge of the lane of travel.

C. TRANSMISSION MEDIA

Some of the light transmitted towards the driver's eyes is absorbed by the media through which it passes such as eyeglasses, contact lens, the windshield, or atmospheric weather conditions. This absorption of light by the transmission media has little effect on visibility when overall illumination in the field of vision is high; however, under conditions of low illumination, such as are found at twilight or at night, visual efficiency may be dangerously reduced because insufficient light is available to give maximum visual acuity.[229,284] At these low levels of illumination prevailing at twilight or at night, a small decrease in the amount of light transmitted to the eyes may reduce seeing distances below safe stopping distances or reduce visual efficiency to such an extent that driving at normal highway speeds would be extremely dangerous.[227] It should be emphasized, however, that the eye is subject to considerable differences between individuals and that small differences in the natural make-up of the eye cause significant physiological differences in visual efficiency under the influence of various levels and types of lighting conditions.

The use of tinted materials in eyeglasses, contact lenses, or windshields reduces the luminance by removing the light or one or more colors.[168,229] Tinted materials may improve vision when color contrasts contribute to visibility; however, as darkness falls, color contrasts disappear except for bright light sources and signs.[225,226,228,229] In a study conducted by General Electric Company, it was concluded that with opposing glare present seeing distances with or without tinted glasses were not significantly different, but without opposing glare there was a reduction in seeing distances with the glasses.[187] Although visibility of objects in the illuminated area of the glare source which are viewed with the aid of tinted materials may be approximately equal to visibility without the use of tinted materials, there is a general loss in vision in all other areas of the field of vision where illumination is low.[229,284] In addition, the loss in vision due to these tinted materials increases with the age of the driver.[229]

The reduced vision caused by tinted materials depends upon the amount of light absorbed by the material and this, in turn, is determined to a large extent by the thickness of the tinted material.[229] Such materials, including yellow, have been found to reduce vision at night by about the same amount as that absorbed by the material.[284] For many tinted materials, this loss in vision may amount to 15 to 30 degrees.[224] In a study by E. Wolf, R. A. McFarland, and M. Zigler it was concluded that tinted windshields with 65 to 70 per cent light transmission had a slight effect in reducing visual acuity and that depth perception was reduced in the range of 25 to 30 per cent at various levels of luminance.[284]

Tinted glasses or contact lenses should be prescribed by a competent visual specialist on an individual basis; otherwise, tinted glasses or lenses should not be worn at night.[224] However, there does seem to be a favorable psychological effect produced by yellow glasses as shown in a study made in Los Angeles where a majority of the drivers involved reported that the glasses were helpful in driving.[172]

A number of different devices have been used to improve vision under adverse atmospheric weather conditions. At one time it was thought that yellow light would reduce the adverse effects of fog, haze, and scattered light; however, it has been shown that yellow light provides no advantage under these conditions and, in fact, reduces vision to a lower level.[224] Yellow glasses and other tinted materials have not been shown to be effective in aiding vision in the presence of adverse weather conditions such as fog. A considerable amount of data on the light scattering effect of fog has been accumulated and used to show that vision can be improved by using a new concept in street lighting design.[210] ● ●

III. FACTORS INFLUENCING EFFECTS OF GLARE

A. HUMAN FACTORS

The previous chapter was devoted to a discussion of the factors which influence the amount of light incident upon the driver's eyes, thereby affecting night vision. These factors, however, constitute only part of the total problem, because the physiological and psychological state of the driver and the specific obstacle conditions also influence the driver's seeing distance at any given instant. Consequently, the factors influencing the extent of the human reaction to the light incident on the eye must also be considered in evaluating the problem of night visibility.

1. Age

One factor which has an important effect upon night vision is the driver's age. This factor is important both because an increasing number of drivers over 65 years of age continue to operate motor vehicles, and because many physiological changes occur during the aging process. B. W. Marsh[188] has stated that there were four times as many drivers over 65 years of age in 1959 as in 1940. Moreover, other statistics indicated that the number of drivers in this age group was increasing at a much faster rate than the group of drivers below 65 years old -- a trend which is expected to continue.[188] An increase in the number of drivers in this age group, however, would not be considered a problem if the accident involvement rate was low, but this rate is substantially above the involvement rate for all age groups, except those drivers under age 25.[188] Thus the influence of a driver's age must be considered in both highway planning and highway design.

Of equal or greater importance to the number of older driver's which operate motor vehicles, is the effect age has upon various physiological functions which influence the individual's night driving ability. Even though considerable overlap between age groups is to be expected, many studies have found distinct physiological changes as age increases. E. Wolf[281,282] studied the changes in glare sensitivity of individuals ranging in age from 5 to 85 years. The subjects were required to identify the gaps in Landolt rings located at 4 degrees, 7 degrees, and 10 degrees from the glare source as the background luminance was varied from 2.5×10^{-4} to 27.5 millilamberts and the glare source luminance was varied from 1 to 15,000 millilamberts. The results of tests on 200 subjects showed a definite demand for higher target screen luminances, at a specific glare luminance, as age increased. With subjects grouped into ten-year age intervals, the shift in the target screen luminance demand was not constant, which indicated that the luminance requirements for seeing the target under conditions of glare "was not directly proportional to age." The test data indicated that the luminance demand rose slowly up to 40 years of age, where a change in slope occurred. Between 40 and 85 years of age the luminance demand was much greater. This increased difficulty in the ability to see under glare conditions was attributed to the changing opacity of the lens in the eye, which occurs as age increases.[281,282]

In another study, R. H. Peckham and W. M. Hart[206] used the critical flicker frequency method to relate retinal sensitivity to age. Using a 5 per cent flicker contrast, 100 persons, ranging in age from 13 to 80 years, were tested. Differences between the flicker rates of various persons were "interpreted as retinal sensitivity, i.e., as estimates of the effective brightness of the field." On this basis, the authors concluded that when compared to the median age group (32 to 50 years of age), illumination of a headlamp beam was at least six times more effective for about one-third of the teenagers (age 13 to 19 years) and young adults (age 20 to 31 years), and at best one-sixth as effective for greater than one-half of the oldest group (age 51 to 80 years). Thus a range of 36 to 1 existed in effective brightness between the teenage and oldest age group.[206]

The authors[206] also concluded that those drivers above the age of 50 years should exhibit extra caution when driving at night, and older drivers should avoid night driving "as a matter of survival." Moreover, study of the data from selected individuals involved in these tests indicated that extended exposure to sunlight greatly influenced their retinal sensitivity under low illumination levels. Consequently, the use of sunglasses was encouraged for those individuals who must be outdoors during the day and who must drive at night.[206]

R. A. McFarland and R. G. Domey[189] performed a study on 474 men and 806 women ranging in age from 15 to 89 years of which one-fifth were age 50 years or more, aimed at determining the illumination threshold at which a test target becomes just visible and the change in illumination required to make the same target just visible under glare conditions. The glaring intensity represented the intensity of vehicle headlights located at 100 to 150 ft away, and the angular separation was equal to that between a vehicle at 150 ft and a pedestrian walking along the right edge of a 20-ft-wide pavement. The test scores were found to increase with the subject's age, the increase being slight up to age 50, quite pronounced between the ages of 50 and 70, and very pronounced above the age of 70 years.[189]

The authors[189] also summarized several studies which correlated dark adaptation, night vision efficiency, and pupil size with age. The people tested in these studies varied in age from their teens to well into their seventies and eighties. In most cases, the specific function was at least in part correlated with age in such a fashion that a decrease in the subject's night driving ability could be expected as age increased, especially in subjects older than 40 to 50 years.[189]

2. Visual Ability

Another factor which greatly influences visibility is the visual ability of the driver. The visual ability of any person driving at night is denoted by several important visual functions which include depth perception, glare sensitivity, dynamic visual acuity, contrast sensitivity, static visual acuity, glare recovery, dark adaptation, and peripheral vision. While these factors do not necessarily represent a complete list of all possible visual functions which influence night vision, they represent the functions most frequently mentioned in the literature in connection with operation of an automobile under night levels of illumination.

Depth Perception

As stated by O. W. Richards,[227] the decrease in the number of visual stimuli perceptible to the driver at night creates a reduction in stereoscopic vision, i.e., depth perception, which causes estimates of distance and relative speed to be made with greater difficulty than under daylight conditions. R. A. McFarland and R. G. Domey[189] mentioned a study in which an average reduction in stereopsis of 25 per cent occurred in the test sample when the illumination was reduced by 30 per cent. Moreover, in another study of differences between accident-free drivers and accident repeaters, the accident-free group had significantly better depth perception, along with superiority in other visual functions.[189] Consequently, McFarland and Domey[189] concluded that if a motor vehicle operator is to have the necessary degree of control over the actions of his automobile, reductions in depth perception should be avoided.

In an attempt to delineate the variables which affect perception of relative motion under mesopic vision, H. I. Stalder and A. R. Lauer[258] performed a study to determine if driving speed and the distribution of pattern detail were important influencing factors. Using a scotometer, designed to represent the visual environment of an actual highway, five vehicle speeds, appropriately scaled to fit the model ranging from 10 to 50 mph, in 10-mph increments, and three target patterns selected in order to compare concentrated and distributed areas of reflectorized material were presented as test variables. The lighting conditions were selected to represent high-beam lights with no glare present and low-beam light facing the same. The variables of perception time, estimation of speed differential, distance estimate, judgment of difficulty, and errors made in the direction of relative target movement were considered in the data analysis.[258] In another study an increase in the visual angle of the visible parts of the target (two rather than one taillight) significantly increased the detection of relative motion.[130]

Based upon the results of 30 subjects, the authors[258] concluded that differential speed was a factor in the judgment of relative distance between two vehicles traveling in the same direction, and that the distribution of pattern detail may have had an effect upon the perception of movement. However, more work was needed in order to draw a definite conclusion. In addition, an increase in target visibility at low illumination levels significantly reduced the time required for both directional and rate of movement determinations, improved the accuracy of estimating actual speed differentials and the stopping distance safety factor -- the latter by causing a more conservative distance estimate of the brighter targets -- decreased the errors in determining directional movement of the moving target. Moreover, if the target was sharply delineated, providing reflectorized areas of equal size it was slightly more effective. Finally reflectorization of vehicle tailgates substantially improved perception of relative motion.

In another study, E. Wolf and M. J. Zigler[285] determined the relationship between glare source luminance and the threshold luminance of a stationary target located at various angular separations from the glare source. In the first part of this experiment the threshold luminances were determined for a constant glare luminance of 2291, 165.2, 17.2, or 2.4 millilamberts, while the visual size of the test field (either 2, 4, 8, or 16 degrees), the visual size of the glare field, the angular separation of the two fields (either 2.5, 5, 10, or 20 degrees was used with the test field appearing to the left or below the glare source), and the test field exposure time (values used were 0.01, 0.02, 0.04, 0.2, and 1.0 sec) were varied. The conclusion indicated that threshold luminances, i.e., target visibility, was dependent upon all of these factors, and that regardless of the visual size of the test field or its retinal location, visibility thresholds decreased with increased angular separation and increased duration of exposure up to one-second duration. If the exposure duration increased above one second or was presented continuously, the thresholds remained constant or increased slightly. Moreover, increasing the visual size of the glare source as well as the glare luminance caused the thresholds to increase.[285]

In the second part of this study[285] three targets replaced the test field, namely gaps in a Landolt ring, letters, and dials, and the target was shown continuously at specific locations on concentric circles located at 4, 7, and 10 degrees from the glare source. Threshold luminances, at which the given target at a specific angular distance could be perceived, were again recorded while glare source luminance was varied in discrete steps from 1.25 to 15,200 millilamberts. In addition, results were obtained for black targets on a white background and for white targets on a black background. Based on these tests, threshold target screen luminance for readability was dependent upon the glare source luminance, the angular separation between the target and the glare source, and the visual size of test targets.

Visual Acuity

Defined by P. J. Bouma,[30] visual acuity is the ability to differentiate between forms of certain objects which are viewed with a small angle of vision or the ability to distinguish as separated entities objects situated close together. It is this second definition with which this report is concerned.

Visual acuity may be influenced by several factors.[30] The relation of background illumination to object illumination is relevant to seeing or not seeing. Under conditions of road lighting, the object illumination is less than the background illumination. An increase in object illumination results in diminution of contrast (as object illumination is made equal to background illumination. An increase in background illumination results in an increase of contrast. Increases in object and background illumination by the same amount increases the visual acuity. This outline does not take into account luminous objects, for which the relationships would differ.

Visual acuity is better for sodium or mercury lamps than for white light, and therefore the physical composition of the light is important.

The distance between the object and the subject has an effect on visual acuity. For distances less than 2 m, visual acuity is directly proportional to distance; between 2 and 7 m, visual acuity is independent of distance, and for distances greater than 7 m, visual acuity is inversely proportional to distance. It is likely that any study of headlight glare and night driving would only be concerned about visual acuity for distances greater than 7 m. Physical characteristics of the subject (myopia, astigmatism, etc.) also influence visual acuity.

From time to time, suggestions have been made concerning night driving glasses which are designed to penetrate fog and reduce glare. The only evidence for such facilitation is the subjective report of wearers, and scientific evidence is negative.[172] A. R. Lauer[168] found that all types of filter glass caused decrements in visual acuity regardless of color or wavelength. Both glare and visual acuity were reduced to the same degree. Although the relation was not linear, there was no indication that filters aid vision at low levels of illumination.

It should be noted that age affects visual acuity, just as it does so many other skills necessary for driving. R. H. Peckham and W. M. Hart[206] found that visual acuity, as measured by critical flicker fusion methods, decreased with age.

Dynamic Visual Acuity

Dynamic visual acuity is characterized by the manner in which a person's visual acuity deteriorates as a function of increasing target speed.[93] It is measured during voluntary ocular pursuit of moving test objects[61] and is inversely proportional to the angular velocity of the target.[61,93,227]

O. W. Richards[227] determined that dynamic visual acuity drops as eye movement exceeds 20 degrees of visual angle per second; the eye can follow speeds up to 60°/sec, but at greater speeds, tracking becomes jerky. Visual correction takes longer because long eye movements undershoot the target and short movements overshoot. Generally agreeing with these numbers, J. E. Goodson and J. M. Miller[93] stated that appreciable deterioration did not occur at speeds less than 30°/sec, and that past this speed the deterioration of dynamic visual acuity was independent of static visual acuity.

In a summary of data from E. Ludvig and J. Miller, J. L. Feldhaus[61] reported that static visual acuity and dynamic visual acuity had no within-subject relationship; they also found great between-subject variability in dynamic visual acuity in terms of deterioration with increasing angular velocity.

In measuring angular velocity of a target, the distance between the target and the subject, and speed were determining factors. At 60 mph and 20 ft from the target, angular velocity is 131°/sec. At this speed, visual acuity has decreased from 20/20 (at 0 mph) to 20/317 to 20/121 depending on the individual subject. At 30 mph and 20 ft, angular velocity is 95.5°/sec and visual acuity is down to 20/154 to 20/70, again varying with the individual subject. It is obvious that at short distances, an increase in speed causes dynamic visual acuity to drop sharply; at 1000 ft, angular velocity for 60 mph is 5°/sec and visual acuity drops to 20/51 to 20/38, the same range for 30 mph, 1000 ft, and 2.5°/sec angular velocity. There is no doubt concerning the definite advantage gained by reducing speed.

Under night driving conditions, field illumination affects dynamic visual acuity and static visual acuity differentially. Five to 10 fc may be sufficient under conditions for static visual acuity, and little is to be gained from increases to levels above 10 fc. On the other hand, dynamic visual acuity is benefitted by increases up to 125 fc, pointing out that night driving conditions cannot be illuminated too much.

Glare Sensitivity

Glare sensitivity has been measured by E. Wolf[282] in terms of changes in field luminance for a given glare intensity and data was summarized earlier in this chapter. Results led Wolf to state that glare is an entoptic phenomenon, with age as the main factor.

Lateral separation of the subject from the glare source influenced glare sensitivity, as reported by L. D. Powers and D. Solomon.[209] A small sample size (N = 5) and large between- and within-subject variability prevented the authors from collecting meaningful quantitative data, although they suggested that the effect of opposing headlights may have been present even at 8000 ft.

In an attempt to relate driving performance to glare factors, R. G. Mortimer[195] set up a highway simulation task. Using steering accuracy as a dependent variable, he varied road illumination, glare illumination, duration of glare, frequency of glare, and road speed. Only the factors of road illumination and duration of glare were significant, although glare illumination and glare frequency interacted significantly with these first two factors. Because no differences in performance between glare illumination levels were found, R. G. Mortimer's dependent variable of steering accuracy should be questioned as possibly insensitive to the independent variables which he was manipulating. He defended his choice of steering accuracy as a dependent variable by claiming that the task of night driving becomes one of tracking the road and maintaining vigilance for obstacles, but no control group to measure variance in daylight conditions was available to compare with his data. This leaves the entire simulation open to question as a measurement relevant to glare sensitivity and night driving.

Contrast Sensitivity

The ability to perceive objects in the field of vision is largely dependent on the amount of contrast between the objects and the background. When contrast is very small, objects are not perceived at all.[26] In the night driving situation, excess glare light reduces both contrast and seeing.[227] Thus a person's sensitivity to various degrees of contrast is an important visual factor. By way of definition, if a brightness of value $H + \Delta H$ can still be distinguished from a brightness H, the ratio $H/\Delta H$ is termed the contrast sensitivity.[26] It has been found to be nearly constant over a wide range of brightness values, H.[26]

The human eye may be regarded as an instrument for measuring brightness values. It is capable of perceiving a range of brightness values -- levels of light differing from each other by a factor of 10^8 or 10^{10}.[26] The eye can change its sensitivity to brightness. This is usually accomplished involuntarily (1) by altering the diameter of the pupil, which takes about one second to occur and (2) by changes in the properties of the retina with changes in illumination intensity.[26] Studies by E. Wolf[282] indicated the eye physically undergoes some changes which make it more difficult to cope with glare. This was concluded when it was noticed that sensitivity curves made a sharp break at age 40.[282]

Contrast sensitivity depends on several factors including brightness, color of the light, size and shape of the two fields, and individual differences.[28] At lower and very high brightness values, contrast sensitivity diminishes.[28] At lower levels of night driving, contrast is about 1/7 of the daylight vision on all but well-lighted streets and freeways.[227] When related to apparent brightness, however, contrast sensitivity is practically independent of color.

Two important relationships occur between both age and visual acuity and contrast sensitivity. E. Wolf[282] devised an instrument to determine the relationship to age. It consisted of a glare source (15,000 millilamberts, maximum), of 2-degree angle subtense at the center of a circular test field. On the test field, visual targets at various distances and in different radial directions from the glare source were exhibited for identification. A target screen luminance in 10 per cent steps from 0.00025 to 27.5 millilamberts was used in conjunction with Landolt rings (0.3-in. outer diameter, 0.06-in. gap).[282] Testing over 200 subjects from 18 to 85 years old, Wolf found that as age increased, the curves shifted to higher target screen luminance levels, thus indicating greater glare sensitivity.[282] The shift was not the same for each 10-year period, so the increase was not directly proportional to age.[282]

The following table indicates the relationship of visual acuity to contrast sensitivity. The subjects all had good daytime vision.[227]

Light Level	Acuity	Contrast
11 fl	20/15	4.8%
0.1 fl	20/29	25.4%
0.01 fl	20/84	60.0%

The shift from cone to rod vision under low light levels is partly responsible for the above relationship.[227] From a practical standpoint, it can be seen that as acuity and contrast decrease there is reason to demand at least 20/40 daylight vision for people who drive at night.[227]

A. A. Kruithof and H. Zijl[165] indicated further that a rapid increase in contrast sensitivity of the eye occurred when the background intensity was increased to the region of 1000 lux. Also, a study of patients before and after cataracts were removed suggested that the opacity of the lens was responsible for the glare sensation due to the scattering of light.[282]

A. A. Kruithof made a study of the effect of blurred contours or borders on contrast sensitivity. This has relevance during fog or hazy conditions when objects are surrounded by a fuzzy "area of confusion." He found that when both the cones and rods were used in seeing, there was a decline in contrast sensitivity as soon as the area of confusion exceeded a certain width.[164] This critical width was 7 ft, in that up to that width no decline in contrast sensitivity was observed, but then the sensitivity diminshed rapidly to about two-thirds the original value until a width (of the area of confusion) reached 12 ft.[164] For wider areas the contrast sensitivity remained constant.[164]

Closely related to contrast sensitivity is the "richness of contrast" which describes the intensity of stronger contrasts. This richness of contrast depends on the Purkinje phenomenon which is based on the following facts:[26]

(1) The rods give a bluish-grey color sensation, while the cones perceive color differences.

(2) At low brightness levels only the rods register a sensation; at high intensities only the cones register; both register at intermediate brightness levels.

(3) The sensitivity of rods to light has a different relationship to the wavelengths than the sensitivity of cones.

P. J. Bouma found that at a specific apparent brightness, a greater richness of contrast was accompanied by a somewhat greater contrast sensitivity.

Dark Adaptation

Within the range of illumination of 16,000 ml (millilamberts) to 0.01 ml, the cone receptors of the retina function. Below 0.01 ml and down to 10^{-6} ml, the rod receptors, which mediate only gross form and are insensitive to color (as opposed to cone vision), take over the task of seeing.[190] The rate of dark adaptation for the two receptor systems is quite different; the cone decay curve reaches asymptote in 4 to 6 min while the road adaptation takes more than 20 min. The rate is a function of duration, intensity, and wavelength of the impinging light, and only a fraction of a second of exposure to moderately high luminance will destroy any dark adaptation that takes place up to this time.[190]

R. A. McFarland, et al.[190] reported that night driving takes place under conditions varying in luminance from 0.0028 ml to 3.176 fl, a range which includes both rod and cone functioning. Age has an immediate and direct effect on dark adaptation efficiency. Threshold intensity is significantly higher for older subjects and the effect is more pronounced over time of adaptation. Therefore, any device such as tinted windshields, sunglasses, etc. that reduce the liminance to rod-level vision (less than 0.01 ml) will affect judgments of movement and velocity. Rod-level luminance will be reached faster for older people.

Glare Recovery

The amount of time needed to recover from the effects of glare sources such as those found in the night driving situation increases when the signal-ground contrast is low, when glare intensity is high, or when the glare is of long duration.[156,243] However, studies concluded that in the driving situation, these factors did not increase readaptation time to any significant degree. By using an eye marker camera and a test object mounted on a pendulum, it was found that subjects were able to pick up the target again shortly before the glare source had moved past in the opposite lane. E. Simonson[254] reported to have found a large variability between readaptation times for different subjects. C. W. Brown, L. B. Fisk, and H. P. Torkelson[35] discussed recovery time in relation to vitamin A deficiency. Glare blindness recovered more slowly for subjects on a low vitamin A diet.

In another study by the same three authors[268] high individual differences in recovery time were reported. It was also noted that women took longer to recover than men. A subjective report of difficulty with glare in night driving correlated with longer mean recovery time.

Peripheral Vision

The effect of a glare source impinging on the eye from a peripheral position has implications for night driving since the glare from opposing headlights moves toward the periphery of the visual field as the two cars move closer together. This type of glare tends to reduce the apparent brightness of a foveally-fixated object.[85] G. A. Fry and M. Alpern[85] accounted for this reduction in perceived brightness in terms of veiling luminance produced by stray light falling on the fovea, implying that the effect of a glare source is dependent on stray light. However, other studies (mentioned under the heading of "glare recovery")[243,156] state that recovery from this type of stimulation is fast enough to avoid deleterious effect on the driver.

Physiological Factors

Important to the night driving situation are changes in physiological states that have an effect on visual sensitivity. Oxygen deprivation, insulin hypoglycemia, and carbon monoxide anoxia (from tobacco smoke or automobile exhaust) impair the ability to see dim objects against a dark background.[189] It is pointed out, however, that this task is rarely necessary in a night driving situation.

While anoxia may negatively affect discriminative ability in a laboratory situation, the degree of anoxia produced by smoking had no appreciable effect in a night driving context, as reported by G. Johnsson and G. Jansson.[155] This was measured in a redetection task, using designs that included a small number of measurements on 30 subjects and extensive measurement on two well-trained subjects.

The effect of alcohol on night driving ability, measured by seeing distance, was studied by V. J. Roper and G. E. Meese.[240] Seeing distance under the influence of two "after-dinner" drinks was consistently lower than the no-alcohol group, but this difference amounted to a maximum of 20 ft out of 250 ft, which is a reduction of the seeing distance by 8 per cent. No statistical evidence for this effect was reported, although the investigators commented, "...incidentally, none of the participants [an unreported number] felt that they were at all under the influence of alcohol, yet their seeing distance was reduced." Granted that the data show the alcohol curve below the no-alcohol curve, conclusions about the effect of alcohol on seeing distances are not warranted without knowledge of the number of subjects or number of observations per subject. It is possible that the reason the subjects reported no feeling of the influence of alcohol was that they were not under the influence of alcohol.

3. Fatigue

Fatigue has been defined as the diminished capacity for work or activity.[159] It is important in its relationship to the driving activity and with respect to the effect of glare on fatigue. Two types of fatigue have been identified. The first is fatigue whose effects are quickly reversible and is called subjective or "psychological" fatigue.[67] The second is fatigue whose effects are relatively long-continued, termed physiological fatigue.[67]

Visual factors have long been shown to be of importance in inducing driver fatigue.[67] The constant use of the eyes under uncomfortable conditions contributes to fatigue.[159] Certainly these uncomfortable conditions include glare and faulty illumination of other types.[159] Other factors include brightness contrasts and bright light sources in the periphery of vision.[67] These factors induce fatigue particularly if these light sources are continually changing or moving.[67] Size differences (aniseikonia) suppressed in the familiar daylight geometry can be released from the lack of integrating clues at night.[227] This will distort the driver's seeing and fatigue will increase, leading to greater stress and possible inattention.[227]

Symptoms related to the eye are usually evident when fatigue arises. In one study[67] sleep-deprived subjects (number of hours of deprivation not reported) showed more eye blinks during the driving period than when driving under normal sleep schedules.[67] [Drowsing occurred in 9 of 10 cases in less than 3 hours of driving for the sleep-deprived subjects.[67]] Results of tests of interstate truck drivers revealed that the men who had driven the longest had significantly slower eye movements than those who were well rested.[159] Also, the longest hours-of-driving groups took the longest time to recover from the effects of glaring light in a laboratory test.[159] In another study the number of eye closures and eye blinks was found to increase with time for sleep deprived subjects.[70] The values were significantly higher for sleep-deprived subjects over non-deprived subjects.[70]

Visual fatigue originates in the intrinsic or extrinsic muscles of the eye, in the retina, or in the central nervous connections of the visual apparatus.[159] It results from the fatigue caused by the eyelid and associated muscles trying to hold the lid partially closed to reduce the dazzle from glare.[224] Earlier fatigue is thus evident at night because the inadequate or abnormal muscle balance cannot be held in check at night by the lesser field of vision clues.[227] Also, glare causes more peripheral muscular tension.[16]

More specifically, excess glare light from oncoming headlights increases fatigue because of the stress effects on the ciliary process as the pupil tries to lessen the overall lighting on the retina while at the same time trying to increase the brightness of the image.[16] The accommodation also fluctuates, trying to find the best focus for the inadequate image on the retina.[16] It has been found that the effects of severe glare can be measured by monitoring the muscular action potentials (electrical activity) at different parts of the body.[247] An increase in action with increase in glare may prove to be a general indicator that glare causes fatigue.[247] Another part of the mechanism leading to physiological fatigue is the tendency of the eye to turn reflexly toward a bright source.[66]

How this fatigue from glare (or other factors) affects the driver's ability to function is a topic worthy of brief comment. Persons engaged in long drives have been found to exhibit a loss of effectiveness in certain sensory discriminations, association processes, and motor reactions similar to those required in driving.[159] (The extreme is when the driver dozes off, which was found to happen to 4 of 5 subjects in less than 3 hours of driving after they had been sleep deprived for 24 to 36 hours.[70]) Long drives tend to decrease hand-eye coordination and, as mentioned previously, to decrease visual efficiency.[158,189] Reduced efficiency often persists for several hours.[189] Fatigue was shown to affect airplane pilots' response not in the keenness of visual discrimination, but in alertness and speed of corrective action.[67]

Glare in the visual field also produces marked pain and discomfort.[16] Under fatigue conditions the discomfort threshold may be lower and the effect on the driver even more important than when he is in a more normal state.[16] In conclusion then, it is important to note that proper eye care is essential so that body and eye muscle functions do not have to compensate for defects of the eye and thus add to the fatiguing effects of glare caused by normal eye and body muscle reactions.[227]

B. TARGET FACTORS

To adequately determine the effect of glare on seeing distance it is necessary to select an object or target which it is desirable for the driver to be able to see in time to stop if necessary. The type of target used in past glare studies varies as do the conditions under which the targets were used.

The important factors with regard to targets include: size, shape, reflectance, and contrast; position and location; and other related items.

1. Size, Shape, Reflectance, and Contrast

The most common target, used in numerous studies, was a human-sized dummy designed to simulate a pedestrian (see References 12,21,54, 55,64,65,157,174,236,238,243). The reflectances of these dummies ranged from 3 per cent to 20 per cent,[27,236] although the reflectance of dark clothing was found to be 2 per cent.[108]

The validity of using this type of target has been disputed. D. M. Finch and J. D. Palmer believed that smaller targets (12 to 18 in.) should be used for evaluation purposes.[65] V. J. Roper and E. A. Howard, however, felt that a pedestrian in dark clothing should be the standard, contending that headlamps capable of disclosing this target would be adequate to provide reasonably safe visibility of practically all other hazardous obstacles.[238]

Another common target simulated a small animal such as a dog.[21,222,235,239] H. R. Blackwell, et al., studied nine different targets ranging from a hole in the pavement to an old automobile. The study concluded that a man-sized dummy (20 per cent reflectance) and a small black dog were the two best target types.[21]

Rectangles, circles, and other geometric shapes have also been employed as targets. (See References 54,65,108,124,141,153,154,183, 194,218,220,222,235,239,249.) The principle dimensions of these targets ranged from one to two feet and the reflectances varied from 6 per cent to 11 per cent. A disadvantage of these targets was that they were planes and did not have the characteristics of solid objects particularly with regard to the reflectance of opposing vehicle headlights off certain surfaces of the object at small angles. The solid geometric shapes which have been used included octagonal section solids[65] and cylinders the size of a man.[13,157,243]

Other targets which have been employed include: a wooden "A," 2 ft high;[74] flashing warning devices;[131] child-size dummies;[55] small objects such as tool boxes and boards;[120] red retro-reflectors from cars;[249] and 16 ft by 6 in. white-beads-in-paint pavement markings.[249]

With regard to the contrast of the target with the background, only one study attempted to control the background illumination in full-scale road tests.[137] This control, however, was exercised only in the vicinity of the target. H. C. Dickinson[55] found no effect with respect to the overall background illumination in that results on nights with and without moonlight did not differ.

2. Target Position and Location

The location of the target determines, in part, its visibility. Studies have indicated that the glare effect decreased as the angle between the glare source and the target increased.[124,285] Therefore, a target on the right side of the road or lane is usually more visible than a target on the left side. This difference is further magnified in that the asymmetrical headlight beams are aimed to the right.

Silhouette seeing must also be considered, however. An object can be silhouetted against the opposing cars headlights, atmospheric glow from headlights, or the reflection of the headlights off the pavement. K. Rumar concluded that on a straight 2-lane road, silhouettes are rarely seen closer than 3 ft from the right edge of the road.[243] When the opposing car was over 650 ft away, he found that silhouettes could be seen only when the object blocked the oncoming headlights.[243] [To combat this, M. J. Allen proposed a side-light system to make silhouette seeing more useful.[2]]

The placement of the targets was on the right side of the road in most studies.[13,108,141,235,236,249] H. C. Dickinson stated that the visibility of the road shoulder on the right was of more concern to the driver than the possibility of obstructions in the traffic lane.[55] J. R. Fries and L. J. Ross[74] and V. J. Roper,[236] however, placed targets to the left of the traffic lane. Obviously, targets should not be placed in the lane itself due to the possibility of causing an accident.

3. Other Related Items

When studying a driver's sight distance during field tests it is important to realize the relationship between visual perception and recognition. R. H. Peckham pointed out that to prevent an accident, the driver must not only visually perceive the situation, but he must also psychologically and experientially recognize the danger involved.[205] There is also "the interaction of the basic visibility and the driver's subjective estimate of that visibility," according to A. J. Harris.[111]

Considerable attention has been directed at these matters in sign visibility studies, where reading the sign is more important than seeing that a message exists.[6,7,60,66,68,173] Studies revealed that certain letter heights were necessary to enable drivers to read the signs at specified distances (1 in. of letter height for every 50 to 90 ft of distance).[7,60] It was also learned that above a certain level of illumination, signs became less legible. An optimum level of illumination for best visibility was found to be between 10 to 15 fl.[6,60]

To account for the recognition as opposed to just the visibility of targets, several studies employed more complicated displays. For example, Landolt rings have been employed as targets to test whether the subject could detect the position of the gap in the ring.[222,282,285] In two other studies, subjects were asked to identify the target as a circle or a rectangle[141] and to identify whether the long sides of a rectangle were oriented horizontally or vertically.[137]

The dynamic aspect of the target is a final factor worth mentioning. In a study by C. H. Rex[222] the exposure of the target was regulated to obtain a dynamic effect. He found that twice as much light was needed for a 1/6-second exposure than for a continuous exposure. ● ●

IV. SUGGESTED METHODS OF ALLEVIATING GLARE

A. POLARIZED LIGHTS AND OTHER LIGHTING SYSTEMS

Obviously by increasing headlight output intensity, seeing distance will be increased but at the expense of increasing the glare for oncoming drivers. P. L. Connolly[41] has reviewed the improvement in headlighting systems over the last 30 years. Improvements in headlight design during this time have increased overall seeing distance by as much as 100 ft while keeping glare to a "minimum." Although definite improvements have been made, disability glare still exists and sight distances do not always exceed safe stopping distance for posted speed limits.[74,153,157,238] There seems little doubt that, while continued improvements in conventional headlight design will increase seeing distance further still, they will never be able to reduce headlight glare by significant amounts. One of the largest problems associated with current headlamp design is the effect of misaim of headlights which can cause a serious problem.

Of the means available at present, polarized headlighting appears to be the most promising in terms of headlight glare reduction. V. J. Jehu,[142,143,149] V. J. Roper,[234,242] and others have argued for the introduction of polarized headlighting and have indicated that seeing distances could be maintained at the level of current high-beam systems while glare could be reduced to a fraction of that present with low beams.

Polarized headlighting has failed to be introduced for three major reasons.

(1) V. J. Roper[234] has indicated that the transition period for the change to polarized headlights would require at least five years. During this transition period, motorists without appropriate equipment would be subject to increased amounts of glare.

(2) Polarized headlighting is a relatively inefficient system and would require 3 or 4 times the source intensity of current systems. This would require heavier wiring and a better power source than in present automobiles.

(3) Pedestrians would be subject to intolerable levels of glare since a polarized system would produce a greater light intensity.

Despite the above criticisms polarized headlighting deserves greater consideration for it is one of the most obvious and practical means of reducing glare available at the present time.

B. HIGHWAY LIGHTING

If daylight were present 24 hours a day, there would be no significant glare problem, because the glare sensation exists only when there is within the field of vision a light source of much higher intensity than the surrounding area. Therefore, by increasing the amount of illumination on the roadway, a larger amount of glare is needed to obscure an adequate view of the road ahead. Thus a given set of glare sources (the headlights of oncoming cars) will not cause as great a reduction in seeing distance if the illumination on the object is increased; of course, economic considerations would prevent lighting a highway to daylight conditions. The main problem in the use of highway lighting is to find the point where the proper balance between costs and benefits is achieved.

W. P. Walker[280] stated that the final criterion of lighting installations should be the effect on safety as revealed by before-and-after accident studies. A. S. Fowle and R. L. Kaercher,[71] on the other hand, stated that visibility distance is the ultimate result of street lighting. The safety benefits of highway lighting are discussed in many papers (References 15,64,187,200,210, 215,218,280) and are given added importance by J. M. Waldram,[277,278] who stated that headlights alone do not provide enough illumination for emergency situations.

C. H. Rex[217,218,220,221,222,223] has written extensively on the benefits to be derived from fixed roadway lighting. He has listed[218] benefits under the categories of comfort, convenience, safety, and economy, and has also discussed the problem of determining the relative importance of these categories. In listing economy as a benefit, it is thought that good lighting will stimulate more nighttime activity, and hence increase the consumption of additional goods and services, thereby increasing the gross national product. C. H. Rex has also talked of giving numerical values to lighting benefits using relative visual comfort ratings, relative visibility ratings, and general lighting effectiveness ratings. Benefits discussed by other authors include less driver tension,[39] better visibility,[217,220,221,256] and better visibility of signs.[60]

A question in the design of highway lighting facilities is whether to use silhouette seeing or to provide direct illumination all along the highway. With silhouette seeing, the object is seen only because it blocks light from a brighter area such as the pavement surface. Three papers[15,59,260] stated that silhouette lighting may be more efficient than direct lighting; however, it has also been said that direct lighting is much superior to silhouette lighting.[15,72] J. M. Waldram[276] mentioned glare problems caused by highway lighting designed to make use of silhouette seeing. Two papers[118,276] discussed the relation of pavement reflectance to silhouette seeing.

There is no general agreement as to which roads should be lighted, but both U.S.[200] and British[15] studies have indicated that there is little justification for lighting rural highways at present traffic volumes, even on freeway-type facilities.

While highway lighting produces many benefits, it also produces problems. Probably the most serious of these problems is the glare caused by the lights themselves. See References 59,71,72,115,125,215,216,218,260, and 276 for a discussion of this difficulty. One study reported that the glare created by the highway lighting cancels 50 per cent of the visibility created by the lights. Since one of the main reasons for highway lighting is to reduce the effects of glare, it is certainly important that the glare from the lights themselves be controlled. One method for doing this is to use cutoffs or other means of controlling low-angle light distributions (angles are measured down from a horizontal line through the light source) from the light.[37,72,218,222,260] If the cutoff angle on the light is larger than the angle between the horizontal and the line from the driver's eye to the top of his windshield, the driver will never see the light source and, therefore, will receive no glare. However, if the cutoff angle is smaller than this, an unpleasant flashing will take place as the driver passes the lighting installations. Cutoffs will require highway lights to be closer together or higher than otherwise would have been necessary. Highway lighting lenses designed to throw very little light out at small angles[72] can also be used for a similar glare-reducing effect.

Another solution to the highway lighting glare problem is unidirectional lighting.[272, 273] In this system, the light beam from the highway lights mounted in the median strip of a divided highway faces down the highway in the direction the traffic is moving and is shielded from the view of traffic moving on the opposite direction on the other side of the highway. This system provides all illumination by direct lighting. Since the lights are always behind the driver once they are exposed to him, there is no possibility of glare.

Yet another solution to the highway lighting glare problem is to have the mounting height of the lights below the eye level of the driver and to have no illumination above a horizontal line from the light.[1] Since the lights are so near the roadway, higher levels of illumination are obtained with smaller bulbs. These lights, however, are apt to become covered with dirt or ice when the road is wet or snow covered.

It has been suggested that the use of colored highway lighting might help reduce glare. G. E. Jayle, et al.[135] reported that yellow highway lighting is more comfortable and does not appreciably reduce visibility. However, R. G. Hopkinson[125] reported that no difference could be detected in the glaring effects of yellowish, bluish, and white light, and K. M. Reid[215] could detect no visibility differences among sodium, incadescent, and mercury vapor lights. Another use of colored highway lighting (red) is for danger areas;[64] this idea has been used at many locations in the Los Angeles area.

Another problem created by the installation of highway lighting is the transition from a lighted to a non-lighted section of highway.[218] A driver whose eyes have adjusted to the lighted section may have inadequate vision for a time after driving onto the unlighted section. A solution to this is to have gradually decreasing illumination at the end of the lighted section.

A factor in roadway lighting is the uniformity of illumination. If installations create bright areas below the lights and dark areas between, small but potentially dangerous objects can be "camouflaged" by the non-uniform light pattern.[65] A. S. Fowle and R. L. Kaercher[71] stated that the illumination of the darkest area on the highway should not be less than one-fifth the illumination of the brightest area on the highway.

Another problem associated with highway lighting is maintenance.[59] Bulbs must be changed and lenses kept clean. The new recommended highway lighting practice discussed by W. H. Edman[59] states that lighting design should be based on the most dirt-encrusted condition of the lenses that will be allowed.

The installation of highway lighting increases visibility against opposing glare sources and also creates safety and comfort benefits. While the prime factor preventing greater use of highway lighting is its cost, it also creates the problems of glare from its own lights, transition from lighted to non-lighted sections of highway, and maintenance.

C. MEDIAN DESIGN

There are two answers to the headlight glare problem in terms of median design:

(1) Barriers used in highway medians can block out the light from opposing cars and eliminate headlight glare. Both the planting of trees and shrubs(49,230) and the use of glare fences(62,122,123,267) have been shown to be partially effective in reducing glare. Such a solution may be impractical because the cost of installation and maintenance is high; trees and shrubs need a great deal of care for 2 to 4 years during which time they do not provide effective relief from glare. Also, anything in the median will act as a snow and trash collector and make mowing more difficult; piling snow in the median will break small trees and fences.

(2) The amount of glare decreases with increases in the angle between the drivers' line of sight and the glare source. Obviously, then, if the lateral separation of opposing vehicles is great enough there will be no glare from oncoming headlights. There should be an optimum lateral separation between opposing lanes of traffic such that there is a tolerable level of headlight glare at the driver's eye level. This optimum separation should be greater for high beams meeting high beams than for low beams meeting low beams. This is the solution to be dealt with in the present study.

It should be noted that neither the lateral separation provided by median width nor median barriers constitute an entirely adequate answer to the problem of headlight glare. Only polarized headlighting or overhead street lights can alleviate glare under the worst condition, that of cars meeting on a two-lane undivided roadway. Nevertheless, a great many divided facilities are currently in the planning stage and the determination of the optimum lateral separation which would reduce or eliminate glare on these highways would be an important consideration in the final design. If roads are designed to provide lateral separation sufficient to eliminate glare from opposing high-beam headlights, the later need for costly overhead lighting or median plantings can be eliminated.

In an early study involving median width and headlight glare, V. J. Roper and G. E. Meese(239) found that seeing distance is greatly improved when a 21-ft median is used. Although high beams gave better seeing distance throughout the meeting situation than low beams, the authors suggested that glare annoyance was such as to preclude the use of high beams when approaching closer than 1000 ft. In a more recent study, J. R. Fries and L. J. Ross(74) found that median widths of 60 ft or greater eliminated headlight glare. In this experiment median width was varied from 10 to 100 ft and the tests were run on an unused section of runway.

V. J. Jehu and G. Hirst(153) determined seeing distance for a lateral separation of 10 ft under both high- and low-beam conditions. A single centrally mounted headlight replaced the normal dual beam system. By assuming that the effects of the glaring light on seeing varies inversely as the square of the angular separation between the observer's lane of sight and the direction of the glare source, V. J. Jehu and G. Hirst generalized their results to four additional lateral separations (25, 40, 70, and 130 ft). The authors concluded that median widths of 10 to 20 ft significantly reduced glare from oncoming cars when low beams are used, while a median width of at least 100 ft is needed to eliminate glare from high-beam headlights. A study by I. Goodbar(92) in which he plotted veiling brightness against median width suggested that there may be some glare with medians even as wide as 200 ft although there was little veiling brightness associated with medians greater than 60 ft. L. D. Powers and D. Solomon(209) also reported three preliminary studies on headlight glare and median width. Although no definitive conclusions came out of the studies, the usual relation of increasing sight distance with increasing median width were found.

Using a Visual Task Evaluator, R. N. Schwab[248] has determined a suprathreshold factor for two different objects as a function of high or low beams, lateral separation between opposing vehicles and longitudinal separation between vehicles. Schwab's results indicated that whether low or high beams give better seeing at a particular longitudinal and lateral separation depends on the type of target used; a car retroreflector at 500 ft appears to be more visible with high beams, while a pavement stripe is more visible with low beam configuration. These results point to the danger of generalizing from a single target in research on driver visibility. The expected increase in visibility with increased lateral separations held for both targets with the exception that visibility was greatest under a normal two-lane roadway condition. This finding can be attributed to the testing conditions Schwab used in the experiment.

D. WINDSHIELDS AND OTHER MEDIA

It was once thought that the tinted heat absorption windshields used to absorb heat and reduce glare from the sun during the day would also reduce headlight glare at night. It was also argued that yellow night driving glasses as well as tinted contact lenses would also reduce glare. It has been shown that these media do not significantly reduce headlight glare, but they do reduce transmission of light to the eye which may shorten seeing distance and constitute a safety hazard. (See References 17,120,168,225,229, and 284.)

● ●

V. MAJOR SOURCES OF EXPERIMENTAL ERROR

A. KNOWLEDGE OF TEST SITUATION

Most of the experiments and tests conducted at night to determine seeing distances on the roadway have used subjects who were familiar with the test situation. This familiarity can result in a bias of test results over experiments in which the subject driver was not familiar with the test situation or did not have prior knowledge of the parameter being measured. It has been shown by V. J. Roper and E. A. Howard(238) that drivers who knowingly participate in tests to measure seeing distances normally see the test obstacles twice as far away as drivers who do not know they are participating in tests. Therefore, the attention factor for drivers without prior knowledge of the test has been determined to be 0.5 as compared to an attention factor of 1.0 for subjects who are knowingly participating in tests. Although no evaluation of the attention factor during conditions of vehicle meeting has been made, V. J. Roper and G. E. Meese(236,239) have reasoned that the factor for this situation would be between 0.7 to 0.8 since the driver would normally focus more attention on the roadway when in the process of meeting another vehicle. This attention factor is quite critical and shows that even though there may be sufficient illumination to provide adequate seeing distances during the normal vehicle meeting process, the attention factor of 0.7 to 0.8 reduces the actual seeing distances such that they are considerably less than the necessary safe stopping distances required at normal driving speeds.

B. SPEED AS AFFECTING SIGHT DISTANCE

It has also been shown that changes in vehicular speed has a definite effect upon sight distance. V. J. Roper and E. A. Howard(238) showed by their test results that there is a loss in visibility distance of 20 ft for each 10 mph increment in speed for drivers who were not expecting an obstacle in their path. The spread of observations for each individual, however, was quite large. It was also stated, in regard to this test, that this loss in seeing distance was applicable regardless to beam candlepower and reflection values.

In confirmation of the findings by V. J. Roper and E. A. Howard, J. L. Feldhaus(61) conducted tests which indicated that visual acuity decreased as angular velocity of the test object increased. Thus an increase in vehicular speed would increase relative angular velocity and decrease visual acuity and would result in a decrease in the overall seeing distance.

Laboratory results obtained by H. I. Stalder and A. R. Lauer(258) indicated that judgments of relative speed are more difficult to make when the distances between vehicles were increasing rather than decreasing. This information was very enlightening since it was assumed that the judgment of decreasing distance separating vehicles is more important than increasing distance when driving a vehicle on the highway.

A study conducted in Sweden by G. Johansson and K. Rumar[158] determined safe meeting speeds (for the 0-ft median width). Each of the 413 test subjects drove toward a stationary car (both vehicles on low beams) and was directed to brake when he saw a dark clothed dummy in the middle of the lane adjacent to the meeting car. The median visible distance was found to be 75.5 ft and the safe meeting speeds for this condition were between 16 and 31 mph.[158]

PART II
DISABILITY GLARE FIELD TESTS

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I. INTRODUCTION

Glare may be regarded as a sensation produced by light which enters the eye in such a way as to inhibit distinct vision. Glare is caused by the scattering of light within the ocular media and may produce one of three effects: (1) it may cause a reduction contrast when the glare is superimposed on a visual image (veiling glare), (2) it may cause a dazzling effect (dazzling glare), or (3) it may disrupt the retinal function (blinding or scotomatic glare).[(282)] Glare can seriously interfere with the visibility of an object and greatly reduce seeing distance. In the context of the driving situation, the implications of these effects are evident in terms of safety. It is this disability glare, i.e., that portion of headlight glare which causes a reduction in the driver's seeing distance, which was the concern of the first phase of field testing on the Headlight Glare Project. The critical point occurs when the glare reduces the driver's seeing distance below the level that he needs to be able to stop or avoid hazards on the highway.

Considerable research has been conducted on the problem of headlight glare and the important findings have been previously summarized in this report. Research has determined many of the factors which influence the amount of glare, including such elements as the headlight systems (patterns, aiming, configuration), roadway factors (reflectance, median width, geometrics), and transmission media (tinted glasses, lenses, windshields). Study has also revealed the factors influencing the effects of the glare. These include the human factors (age, visual ability, fatigue) and the target factors (size, contrast, reflectivity, placement). Based on this information, several methods have been suggested for alleviating or at least reducing the amount of glare. The method of most concern in this study is the use of the median to provide lateral separation, because the provision of sufficient separation of opposing vehicles can reduce glare to a point where it would be possible to use high beams to attain the maximum sight distance. This solution is of current interest due to the large number of divided facilities being planned across the nation. It should be noted, however, that neither lateral separation nor median barriers constitute an entirely adequate answer to the problem of headlight glare as was noted earlier (Part I, Section C, Median Design). Only polarized headlighting or overhead street lighting can alleviate glare under the worst condition, that of cars meeting on a two-lane undivided roadway.

In an effort to establish the purpose and the value of the field work conducted by the project staff, it is necessary to cite briefly the current status of research and to evaluate some of the past work. It is important to note first, however, that the physiological bases of disability glare are of ocular origin.[77] Three bases have been identified by G. A. Fry and include: (1) stray light in the eye, (2) pupillary response to light, and (3) adaptation.[77]

Several researchers have attacked the problem of disability glare as related to median width and the major results have been previously discussed. (See Part I, Section C, Median Design.) These results have indicated that the optimum median width is somewhere between 60 to 100 ft, but the investigators found several faults in their test situations. J. R. Fries and L. J. Ross[74] did not get conclusive results because they used only dual lamp high beams, one target, and a relatively poor experimental design. L. D. Powers and D. Solomon[209] had difficulties due to the target type and placement and the driver's visual ability. They suggested that future research employ many tests subjects representing a cross section of ages and visual ability, for older drivers tend to have poorer night vision.

The target type and position were other factors which have varied from study to study and which influence the test results. Results by R. N. Schwab[249] indicated the danger of generalizing from visibility measurements taken on a single target.

Table 1 indicates some of the important parameters employed in the past research. Other than the driver, the most variable element was the target (size, reflectance, and position). Few studies have used multiple median widths or lateral separations (ls, the lateral distance between the test subject and the near side of the opposing glare vehicle). Most studies have been dynamic (moving test vehicle and/or glare source) and in most the age of the subjects was not considered. The number of subjects tested in each study ranged from one to 12.

It was therefore the objective of this study to replicate these previous studies and to extend their scope by employing a multiple factor experimental design. This study was designed to investigate seeing distance as a function of high- or low-beam configuration, lateral separation, age of driver, type of target, and target location. ● ●

TABLE 1.

PARAMETERS USED IN PREVIOUS DISABILITY GLARE STUDIES

Author(s)	Ref. No.	Target: Description	Target: Reflectance	Target: Position	Median Width (or lateral separation)	Beam Type	Test Type	Subject: No.	Subject: Age	Subject: Visual Acuity Checked?
Bergstrom, S.S.	3, 154	145 x 145 mm cloth object, 25 x 115 mm reflectorized tape	6, 11, 25%	0.5m L, 10 cm above surface	0'	F, S_d, A_d	D 15-25 mph	4	N.A.	Yes
De Boer, J.B. & Vermeulen, D.	53	22 cm & up	N.A.	L, R, center		Am, E, high	D	2	37, 46	
Fries, J.R. & Ross, L.J.	74	"A" shape	N.A.	Behind glare source 10 ft R	0' - 100'	Am, high	D 45 mph	7	N.A.	No
Grime, G.	95 96	None 2' x 4.85' & 0.75' x 5'	N.A. 9%	-- Sides & center	-- 0'	Am, high Many, low	D 30 mph D 30 mph	12	N.A.	No
Harris, A.J.	108,109,110	1.5m, 0.4m, 40cm	9-10%	R & L side	0'	Am, E, low	D	1	N.A.	No
Jehu, V.J.	141, 147	cylinder, 1.5' dia & 1.75 x 1' object	7%	10' behind glare source, 10' R	0'	Special	D 30 mph	1	N.A.	No
Johansson, G., <u>et al.</u>	152	dummy 140 x 40 cm (dia) cylinder	6%	1 - 1.75m L @ 40 - 80m, longitudinal distance	0'	A_d, F	D 50 kph	4	N.A.	Yes
Johansson, G., <u>et al.</u>	158	cylinder 30m dia., 1 m high	4%	in lane	0'	E	D 25&37 mph	413	N.A.	N.A.
Powers, L.D. & Solomon, D.	209 (study 1)	car reflector	N.A.	inline	7', 32', 57', 82', (LS)	Am, high	D 25 mph	5	3 @ 20's, 1 @ 33, 1 @ 54	Yes
Powers, L.D. & Solomon, D.	209 (study 2)	car reflector	N.A.	4' L @ 500, 600, 700', longitudinal distance	4', 14', 24', 34', 45', 59' (LS)	Am, high	D 25 mph	3	N.A.	Yes

KEY:

F	Full-headlight (European high beam)	L	Left
A	Asymmetrical beam (A_d = dipped or low beam)	D	Dynamic-moving vehicle
S	Symmetrical beam (S_d = dipped or low beam)	St	Static-stationary testing
Am	American beam (includes S)	LS	Lateral separation
E	European beam (includes F, A, Ad)	N.A.	Not available
R	Right		

TABLE 1.

Continued

Author(s)	Ref. No.	Target			Median Width (or lateral separation)	Beam Type	Test Type	Subject		
		Description	Reflectance	Position				No.	Age	Visual Acuity Checked?
Powers, L.D. & Solomon, D.	209 (study 3)	21" x 28' while transparent plexi-glas screen	variable brightness	900' ahead, 3' above pavement	7', 20', 32', 57', 107', (LS)	Am, high	D 10 mph	2	N.A.	Yes
Roper, V.J.	233	dummy	dark clothes	R edge	0'	Am, low	D 40 mph	6	N.A.	No
Roper, V.J. & Howard, E.A.	238	dummy	dark clothes 2, 7, 14%	Behind glare source, 10' R	0'	A, Am, Low	D	8	N.A.	--
Roper, V.J. & Meese, G.E.	239	18' x 18'	8.5%	Sides	0', 21'	Am, high & low	D 40 mph	6	N.A.	Yes
Roper, V.J. & Meese, G.E.	240	18' x 18'	7%	R edge	0'	A, Am, low	D 40 mph	N.A.	N.A.	--
Schwab, R.N.	249	Red reflector 6' section, while beads on paint stripe	N.A.	500' in front of observing point, 200' in front	12'-112' (LS)	Am, high & low	St	1	N.A.	No
Zechnall, R.	286	40 x 40 cm & 40 x 180 cm	8%	R edge	0'	A, Am	St	6	N.A.	--

KEY:

F Full-headlight (European high beam)
A Asymmetrical beam (A_d = dipped or low beam)
S Symmetrical beam (S_d = dipped or low beam)
Am American beam (includes S)
E European beam (includes F, A, Ad)
R Right

L Left
D Dynamic-moving vehicle
St Static-stationary testing
LS Lateral separation
N.A. Not available

II. RESEARCH PROCEDURE

This discussion of the disability glare field test procedure covers the experimental design, target type and placement, test apparatus, subject description, and the test procedure.

A. EXPERIMENTAL DESIGN

The main experimental design included tests for measuring seeing distance at four lateral separations (6, 33, 72, and 94 ft), two beam configurations (high and low), and eight target placements (see Table 2), with one observation per subject per treatment combination in each of two directions of testing. (See Figure 1.) Each subject made observations under all treatment combinations. The subjects, paid to participate in the study, were male volunteers in the age groups 20 to 30 years and 50 to 60 years; there were five subjects per group.

In addition to the main experimental design, each subject made observations under no-glare conditions for each target placement, both beam configurations and the 6-ft lateral

TABLE 2.

TARGET PLACEMENT

Distance from Glare Source*	Retroreflector (High Reflectance)		Felt-covered Box	
	L	R	L	R
+450			1**	2
-5			3	4
-300	5	6		
-600	7	8		

*(+) sign indicates target placed in front of glare source;
(-) sign indicates target placed behind glare source

** Target number

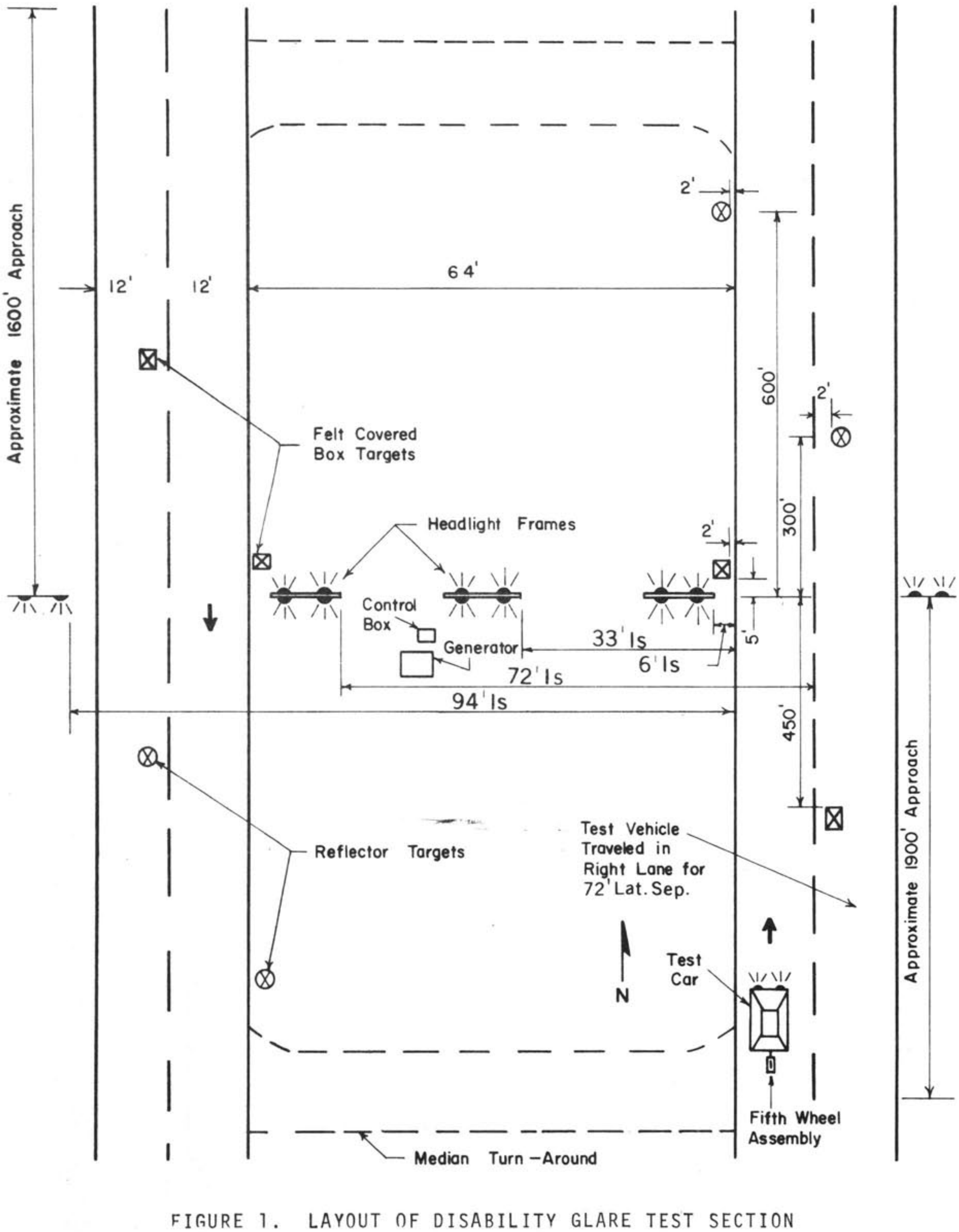

FIGURE 1. LAYOUT OF DISABILITY GLARE TEST SECTION

separation. The effect of polarized lighting was also measured for each target placement, high beams, and 6-ft lateral separation.

B. TARGET TYPE AND PLACEMENT

Two types of targets were employed in the study. The first, a taillight retroreflector assembly from a 1965 Chevelle, was mounted 27 in. above the pavement on a portable wooden stand. The other target was a 16-in. wooden cube, covered with green felt, with a reflectance of 8.5 per cent. (See Roper and Meese.[239]) The targets were selected to represent a wide range of hazards encountered on divided highways. All targets were placed either 2 ft to the left or right of the driving lane.

The longitudinal target placements were chosen on the basis of a pilot study, in which four subjects viewed objects placed in 200-ft increments for 1000 ft in front and in back of the glare source. The final target positions used were a compromise between: (1) the desire to have the target first become visible in the area of maximum glare intensity, and (2) the physical limitations of the test site (length of test section and distance required for the observer's vehicle to accelerate to test speed).

C. TEST APPARATUS

The tests were conducted during the summer of 1965 on a finished but unopened section of Interstate 57 southwest of Champaign, Illinois. The test section, shown in Figure 1, was a tangent, level (nearly constant grade) portion of a four-lane divided facility. Each of the four 12-ft lanes was constructed of portland cement concrete. The right shoulder was 10 ft wide and constructed of a white aggregate surface treatment. The median (including four-foot, surface treatment left shoulders) was 64 ft wide.

The glare sources were standard dual sealed beam headlamps mounted on wooden frames. The frames were positioned in the median or on the shoulder as indicated in Figure 1, and rigidly fastened down with stakes and guy-wires. The design of a typical frame is shown in Figure 2. Once in position, the headlamps were aimed using a Weaver Headlight Tester (Portable Model WX-45), calibrated in the laboratories of Weaver Company, Springfield, Illinois. Low beams were aimed (for the "hot-spot") at 11 in. down and 17 in. right at 25 ft. (SAE specification J579). The high beams were aimed directly ahead and 2 in. down at 25 ft. The intensities of the headlights after aiming were set by a variable rheostat on the generator and checked with the Weaver Headlight Tester. (See Table A in Appendix.)

The glare sources were powered by a 12-volt DC gasoline generator. A control box which contained high- and low-beam switches for each of the eight frames was wired between the generator and the frames.

The seeing distance measurements were obtained from a Performance Measurements Company Model PM-1625 Fifth-Wheel assembly attached to the rear bumper of the test vehicle, a 1964 Chevrolet four-door sedan. The output from this wheel was fed to a control box; a switch on the control box enabled the wheel output to be directed to either of two direct reading electronic counters. Separate switches turned each counter off. A push-button switch (which could be hand-held by the driver) activated either counter, depending on the position of the control box switch. This counting equipment was powered by two DC to AC inverters operating off 12-volt automobile batteries.

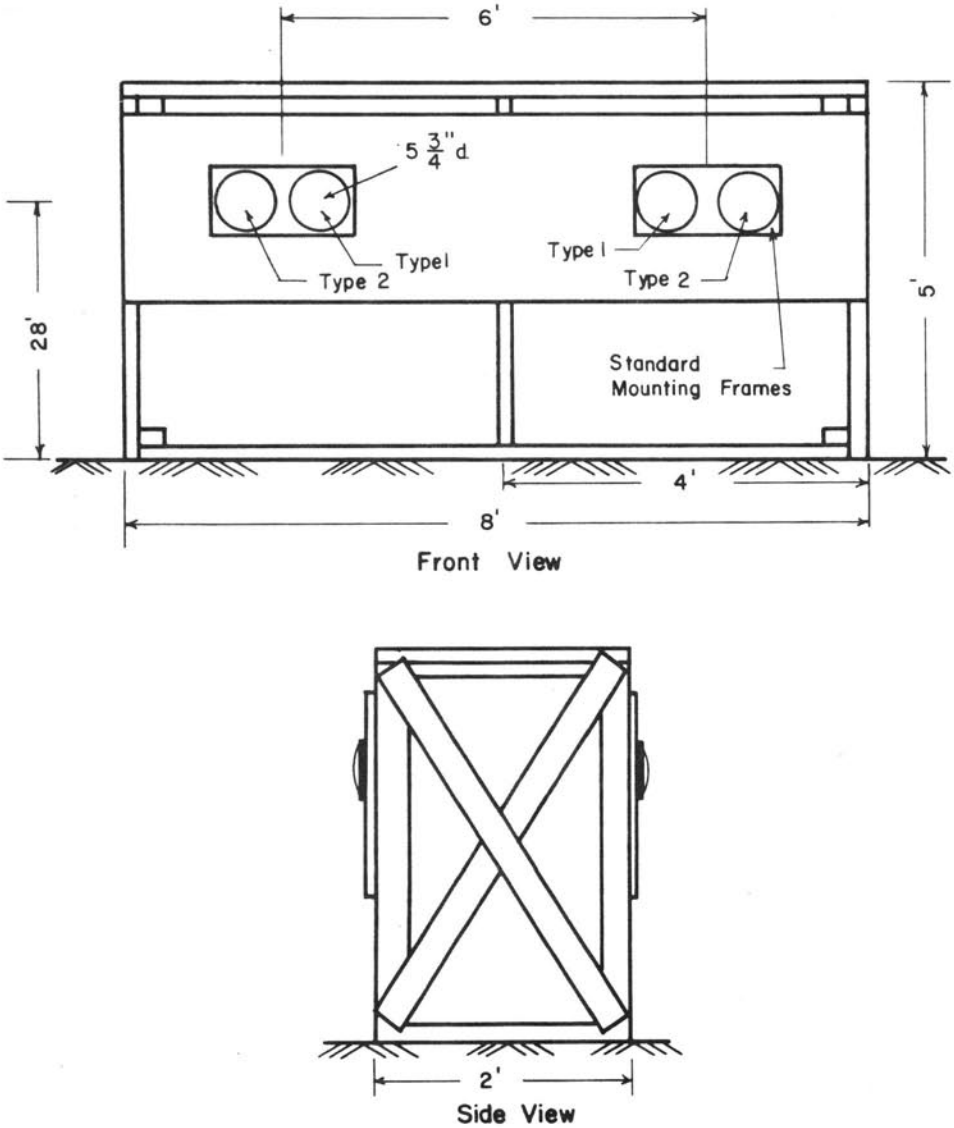

FIGURE 2. TYPICAL HEADLIGHT FRAME

Following the actual field testing, brightness measurements were taken at selected longitudinal distances along the driving lane for the various lateral separations. These measurements were taken with a Pritchard Photometer equipped with an integrating glare lens. The photometer was mounted on a tripod on a three-wheeled dolly at the approximate height of an average driver's eye. Measurements were taken at one-hundred-foot longitudinal spacing intervals up to 1900 ft from the glare source, then at 200-ft intervals.

To test polarized headlighting under the worst glare condition, several test runs were conducted with polarized lighting equipment. The glare sources (6-ft lateral separation only) were polarized by means of linear dichroic polarizing sheets cut into a circular shape which were lowered over the front of the headlight frame by a lever. Thin sheets of polarized material, fastened to plywood frames, were bolted to the grill of the test vehicle and thus provided polarization (mounted 45°-45°) of its headlamps. The subjects (drivers) wore polarized glasses when participating in this test phase.

D. SUBJECT DESCRIPTION

Before field testing began, four tests of visual ability were administered to the 10 subjects (S_s) using a T/O Vision Tester (Titmus Optical Company), and the Night Vision Meter (American Automobile Association) described by A. R. Lauer and E. Allgaier.(171) (See results in Table 3.) All subjects scored close to normal or better than normal on the visual acuity test, but as reported earlier(61) little correlation was found between static (as measured here) and dynamic visual acuity, and so this measure should not be expected to detect differences in seeing ability as measured in the field experiment which involved a stationary target and moving observers.

Glare recovery is a measure of the length of time in seconds for acuity to return after exposure to a bright stimulus. For glare vision and night vision, a low score indicates good vision in that particular environment and both measures are negatively correlated with age. As reported by A. R. Lauer and E. Allgaier,(171) there is no established criterion for glare recovery, and the relationship between age and recovery time is low. Median performance for the two groups of subjects on the glare vision and night vision tests can be compared with representative measures reported in Traffic Engineering Handbook, Institute of Traffic Engineers, 1965, pp. 92-93.

	Young Group	ITE Median	Old Group	ITE Median
Glare Vision	38.3	24.5	54.0	40.2
Night Vision	15.7	13.6	22.7	18.9

Median glare recovery was 3.3 sec and 9.0 sec for young and old subjects respectively. No comparative ITE median values were available for glare recovery.

E. TEST PROCEDURE

Each subject was given a standard set of instructions concerning the purpose of the experiment and what they were expected to do.

TABLE 3.

SUBJECT DESCRIPTION (DISABILITY GLARE TESTS)

Subject Number	Age	Glasses Worn? (for distance viewing)	Type	Snellen Equiv. for vision (20 ft) (corrected vision)	Glare Vision*	Night Vision*	Glare Recovery Sec.
1	26	Yes	Contacts	20/15	44.3	15.3	10.0
2	26	Yes	Regular	20/20	38.3	16.7	3.3
3	23	No	--	20/18	42.0	16.3	3.0
4	20	Yes	Regular	20/18	36.0	14.7	4.7
5	25	No	--	20/13	32.3	15.7	1.8
6	54	No	--	20/13	48.3	18.7	16.0
7	55	Yes	Bifocals	20/13	94.3	39.7	2.3
8	57	Yes	Bifocals	20/18**	100***	62.0	14.0
9	58	Yes	Regular	20/18	29.3	22.7	9.0
10	50	Yes	Regular	20/22	54.0	15.0	8.0

*Average of 3 trials -- Night Vision Tester -- Rheostat Settings

**Subject color blind

***Arbitrarily chosen, subject couldn't get a reading

They were told that on each run past the headlight frames one or more targets (red retroreflector or green cube) would appear to either the left or right of their driving lane. As soon as they saw a target they were instructed to push a button (activating the fifth-wheel counter) and call out the name of the target and its position (left or right), being careful not to anticipate.

Test runs began with the test vehicle, driven by the subject, about 1600 ft from the headlight frames. The subject accelerated to 45 mph and then forgot about speed, according to the instructions. When the subject saw the first target, he pressed the button starting one counter, at the same time calling out the target type and position. An experimenter, sitting in the car with the subject, checked the subject's identification (by a code sheet indicating which target should be in which position for a given run) and also threw a switch readying the second counter. When the subject saw and identified the second target (if one was present) he again pushed the button activating the second counter. When the test vehicle reached the appropriate target, the experimenter switched the specific counter off and recorded the distance measurements. The subject was then asked to rate the glare on a five-point discomfort scale (see discussion in Part III of this report). After crossing the median, the subject ran the test again from the opposite direction.

The procedures used to reduce bias in the subject's observations are listed below:

(1) The subjects were not told how many targets would appear on each run, only that there would be one or more. The subject soon learned that there were at most two targets but sometimes only one. This procedure was intended to reduce anticipation by the subject.

(2) Subjects were asked to identify the targets immediately (both placement and type) to cut down on anticipation and false recognition.

(3) Positions and targets were presented randomly (including polarized and no-glare conditions) to introduce some of the aspects of normal driving although the subjects were probably still more alert than normal drivers because they knew that a target would be coming up.

III. STUDY RESULTS

The results of the disability glare field tests are presented in the following sections below which discuss the overall experimental design, target type and placement, seeing distance and lateral separation, and polarized headlighting.

A. GENERAL ANALYSIS OF VARIANCE

The disability glare data were analyzed with the BALANOVA 5, a general analysis of variance for the IBM 7094 digital computer written by Paul Herzberg, August, 1966, available through the Statistical Service Unit, University of Illinois. The results are shown in Table 4.

Since observations were taken on a closed circular track with two sets of glare sources, it was necessary to use this direction difference as a main factor in the analysis. For each combination of subject (S), lateral separation (L), beam configuration (B), and target (T1...T8), one observation was taken from each direction. This direction (D) factor was the only main factor that was not significant in the analysis of variance, all other main factors being highly significant. All interactions (defined as the extent to which an observation is determined by a combination of factors) involving direction were not significant.* All other interactions, including the A (age group) x L x B x T were significant, indicating that consideration of the problem of seeing distance must include all factors, and that seeing distance is a joint function of all these factors. Before discussion of the four-way interaction, each of the main effects will be briefly mentioned. As might be expected from previous research (see References 23,188,281,282), the younger subjects (Group Y) produced longer seeing distances than did the older subjects (Group O) regardless of target type, beam configuration, or lateral separation. High beams (Hi) provided greater seeing distances than low beams (Lo), as would also be expected. As the lateral separation increased, seeing distance also increased. The eight different targets (T1...T8) produced different seeing distances.

Figure 3 shows the relative stability of each group of subjects across lateral separations. In considering this plot, it should be remembered that each point is the average of all 8 targets, both directions (a non-significant factor) and both beam configurations. The older subjects showed greater variability than the younger subjects, and this variability increased with lateral separation.

Figure 4 indicates that the younger subjects (Group Y) reported longer seeing distances than older subjects (Group O) for all treatment combinations. The difference between age groups increased with the increase in lateral separation.

*Except for the interaction of D x T which seems unexplainable and very small in comparison with the other second order interactions.

TABLE 4.

SUMMARY TABLE FOR ANALYSIS OF VARIANCE

Source of Variation	Degrees of Freedom	F Value	Level of Significance
A	1	22.65	0.005
S	8		
L	3	479.87	0.005
A × L	3	20.67	0.005
S × L	24		
D	1	0.17	NS
A × D	1	0.02	NS
S × D	8		
B	1	522.54	0.005
A × B	1	12.4	0.01
S × B	8		
T	7	442.79	0.005
A × T	7	9.87	0.005
S × T	56		
L × D	3	0.90	NS
A × L × D	3	1.68	NS
S × L × D	24		
L × B	3	383.05	0.005
A × L × B	3	17.34	0.005
S × L × B	24		
L × T	21	43.26	0.005
A × L × T	21	3.19	0.005
S × L × T	168		
D × B	1	0.50	NS
A × D × B	1	1.76	NS
S × D × B	8		
D × T	7	3.77	0.005
A × B × T	7	1.28	NS
S × D × T	56		
L × D × B	3	0.28	NS
A × L × D × B	3	2.37	NS
S × L × D × B	24		
L × D × T	21	1.08	NS
A × L × D × T	21	1.08	NS
S × L × D × T	168		

*Key

A = Age group
L = Lateral separation
D = Direction
B = Beam condition
T = Target
NS = Not significant

TABLE 4.

Continued

Source of Variation	Degrees of Freedom	F Value	Level of Significance
B × T	7	171.79	0.005
A × B × T	7	4.49	0.005
S × B × T	56		
L × B × T	21	19.71	0.005
A × L × B × T	21	2.32	0.005
S × L × B × T	168		
D × B × T	7	0.87	NS
A × D × B × T	7	0.46	NS
S × D × B × T	56		
L × D × B × T	21	0.49	NS
A × L × D × B × T	21	0.93	NS
S × L × D × B × T	168		

*Key

A = Age group
L = Lateral separation
D = Direction
B = Beam condition
T = Target
NS = Not significant

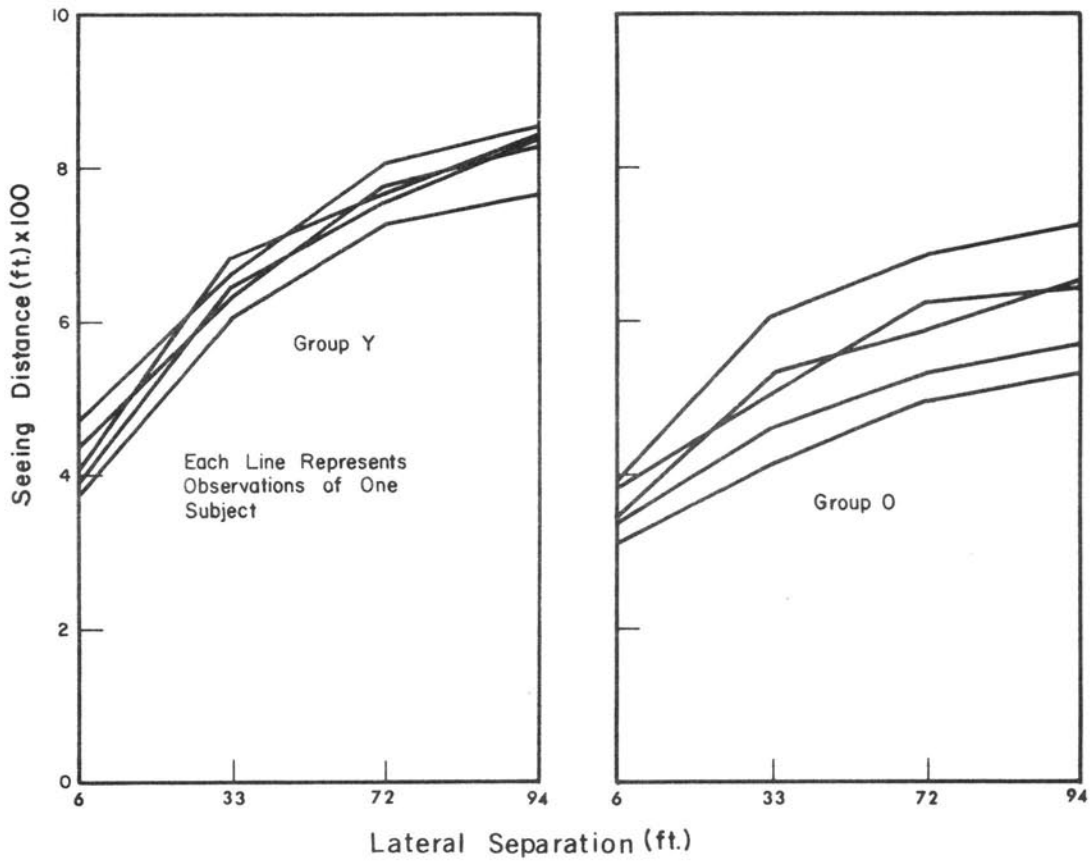

FIGURE 3. SEEING DISTANCE VS. MEDIAN WIDTH, BY AGE GROUP AND SUBJECT

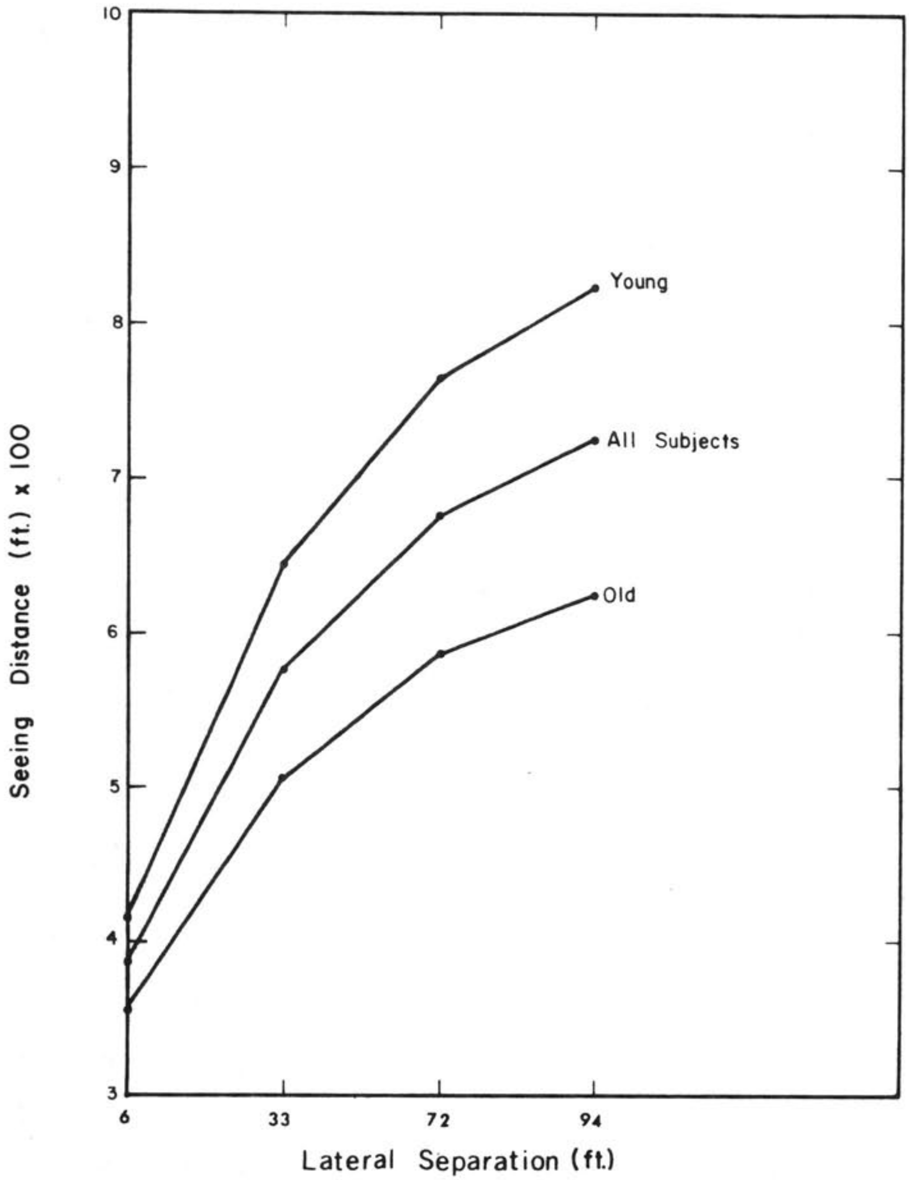

FIGURE 4. SEEING DISTANCE VS. LATERAL SEPARATION, BY AGE GROUP

By classifying the results of Figure 4 into the two beam configurations, Figure 5 shows that, across lateral separations, the increase in seeing distance was much greater for high beams than for low beams. Group Y improved more rapidly than Group O with the increase in lateral separations. With low beams, little improvement was made by increasing the lateral separation. The two age groups maintained a constant difference in seeing distance across lateral separations.

B. RELATIONSHIP OF TARGET TYPE AND PLACEMENT

Although the target factor in the analysis was significant, no statistical method of examining between-target differences was available. To apply tests for individual comparisons, the levels of the factor must be quantitative; that is, one must be able to order them in some fashion quantitatively. With the targets used, distance from the glare source, target type, and target placement were confounded (i.e., the effects due to each factor could not be separated), making conclusions drawn from the data subject to the restriction that the seeing distances obtained apply only for particular combinations of the three factors involved. For example, the high- and low-reflectance targets differed not only in this respect, but also in their distance from the glare source. (See Table 2.) Differences obtained between high- and low-reflectance targets may be due either to this variable or to the distance factor, and cannot be separated statistically. Despite this shortcoming, meaningful inferences could be drawn from the data concerning the relative effect that these differences had on seeing distance. Figure 6 shows the differences in seeing distance associated with target type. Values are averaged over age groups and beam configuration and are not representative of seeing distance in comparison with safe stopping sight distance.

Target reflectance provided the greatest effect on seeing distance, as seen in Figure 6. The separation of the two high-reflectance functions from the low-reflectance functions indicated that for the reflectance used here, target type was a more important factor than distance from the glare source. Discussion of target type must always be qualified by distance, but seeing distance for the high-reflectance targets was increased only by a small amount when the target was moved from 300 ft to 600 ft behind the glare source. Likewise, little difference was seen between the low-reflectance targets at 450 ft in front and 5 ft behind the glare source.

The target placement factor was a function of several sub-factors. The angle of impingement of light from the glare source made targets on the right side of the road more easily seen than targets on the left side. Another sub-factor that was found to be important was the contrast of the target with its background. As will be shown, the contrast factor appeared to be more important for the low-reflectance targets and the left-right placement more important for the high-reflectance targets (with target type qualified by distance from the glare source).

Figure 6 shows that, for the low-reflectance targets, a reversal in trend occurred for targets situated on the left and the right at the 72-ft lateral separation. This lateral separation was provided by driving in the outer, right-hand lane of pavement rather than the inside, left-hand lane that was used for the other three lateral separations tested. The effect of the change in driving lanes was to change the contrast associated with low-reflectance targets on the left and right. For the usual case 6-, 33-,

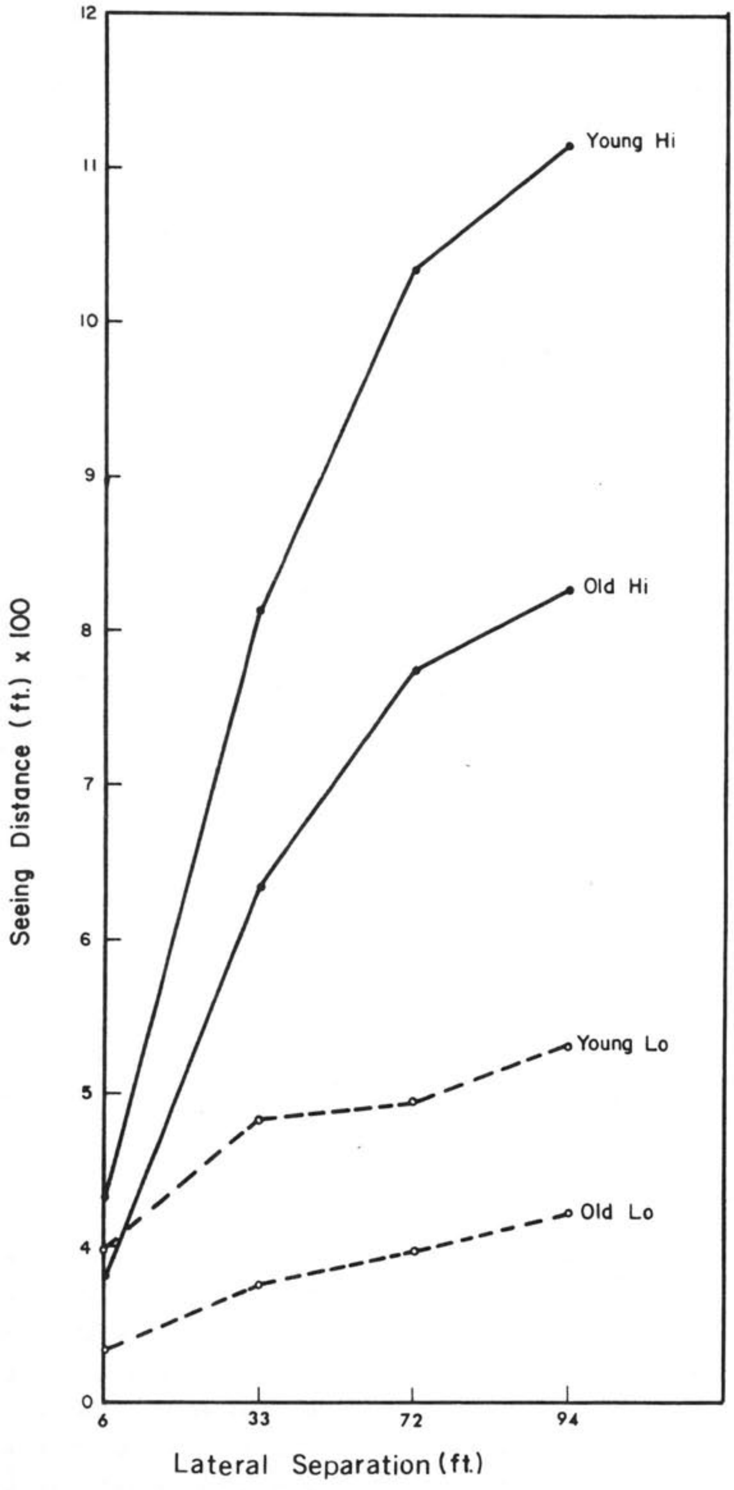

FIGURE 5. SEEING DISTANCE VS. LATERAL SEPARATION, BY AGE GROUP AND BEAM CONFIGURATION

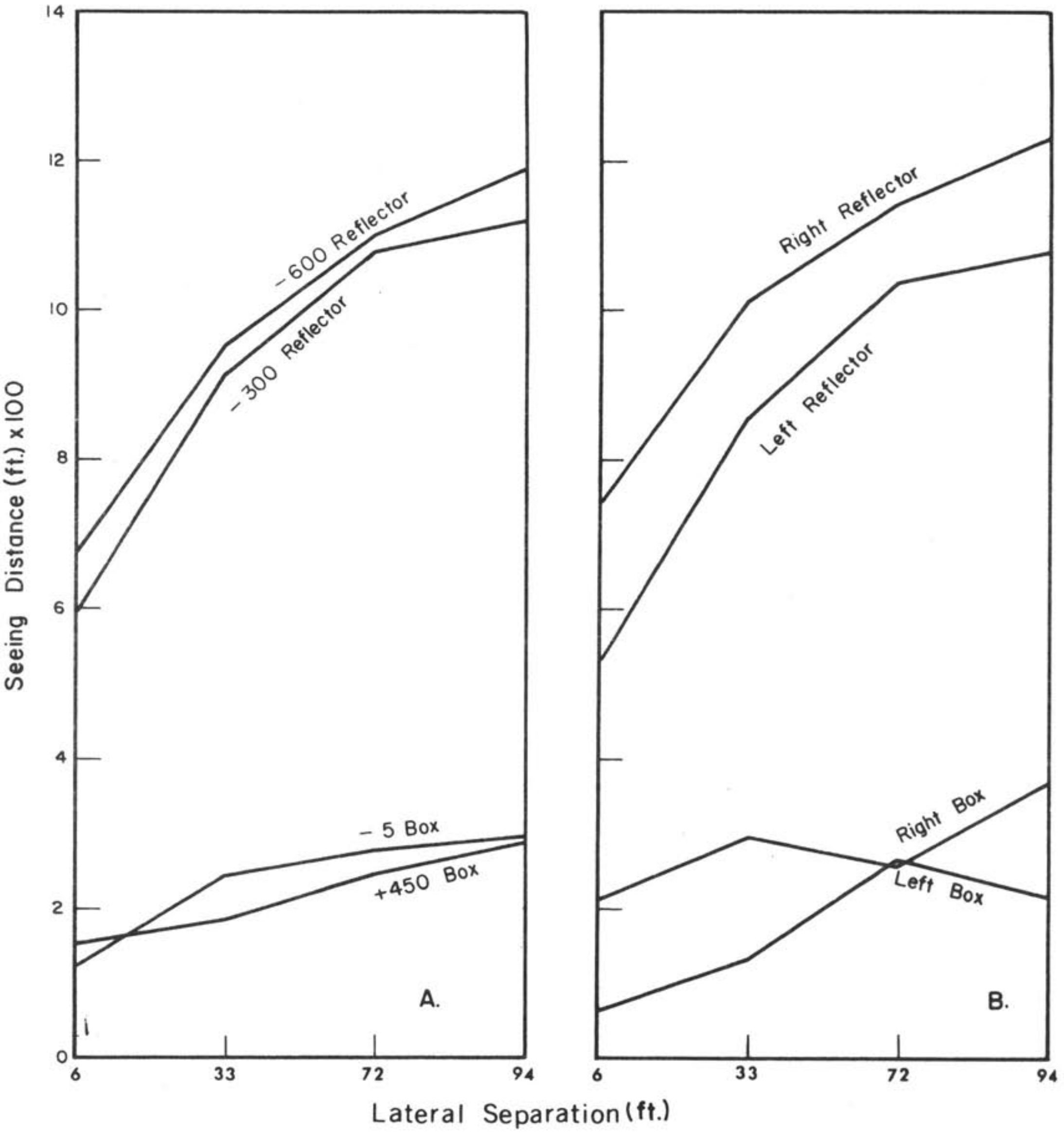

FIGURE 6. SEEING DISTANCE VS. LATERAL SEPARATION, BY TARGET TYPE

94-ft lateral separation the left target was placed 2 ft off the concrete pavement on the shoulder, constructed of a white aggregate material of lower reflectance than the portland cement concrete pavement. The right target was located 2 ft to the right of the inside lane, still on the portland cement concrete pavement surface. Because of its higher reflectance, the pavement surface provided a greater contrast with the target of low reflectance than that of the shoulder with the target. Thus for the 6-, 33-, and 94-ft lateral separation this contrast factor was, in effect, with the target on the right being more easily seen. But when the 72-ft separation was used, the background for the placement of the targets was reversed, with the left target providing greater contrast because of the relatively high reflectance of the pavement surface, while the right target was viewed with relatively low contrast on the shoulder. This switch in target contrast is seen in Figure 6. The point for low-reflectance-left is elevated above its expected position and that for low-reflectance-right is depressed, indicating that contrast had more influence on the seeing distance than did the angle of light from the glare source.

The contrast reversal did not hold for the high reflectance targets, implying that contrast in this case was less important than target placement.

This importance of contrast in determining seeing distance for low-reflectance targets was contrary to the assumptions made by V. J. Jehu,(141) and indicated that target type must be taken into the consideration of the effect of target contrast with background.

Figure 7 indicates the increase in seeing distance afforded by the use of high beams as opposed to low beams, averaged across lateral separation and target types. The use of high beams increased seeing distance about the same for both age groups, and more for the high-reflectance targets than for the low-reflectance targets.

C. SEEING DISTANCE AND LATERAL SEPARATION

Because of the increase in variability of observations with an increase in lateral separation, it was decided that, rather than the mean of the observations for a particular treatment combination, the mean minus one standard deviation should be used as the index of seeing distance, and that this value should be compared with the safe stopping sight distance in order to determine the optimum lateral separation.

All observations were made at a speed of 45 mph. In order to generalize to other driving speeds, it is necessary to determine that the increase in angular velocity does not drastically affect the distance at which a target can be recognized. J. L. Feldhaus(61) discussed the deterioration in visual acuity with increases in speed; for distances and speeds with which this report is concerned, deterioration of visual acuity occurs, but to a level that is still above the lower limit of acceptable corrected vision (20/40 in Illinois). Since recognition is a task that requires less effort than tasks involving acuity, it can be assumed that the results of this experiment can be generalized to include higher vehicle speeds.

The safe stopping sight distances (SSSD) chosen are based on dry pavement conditions. All observations were made on dry pavement and additional factors involved in wet driving conditions (added glare, etc.) make generalizations to these conditions questionable. Table 5 indicates the safe stopping sight distances for several speeds under dry pavement conditions.

Figure 8 shows the mean minus one standard deviation for each treatment

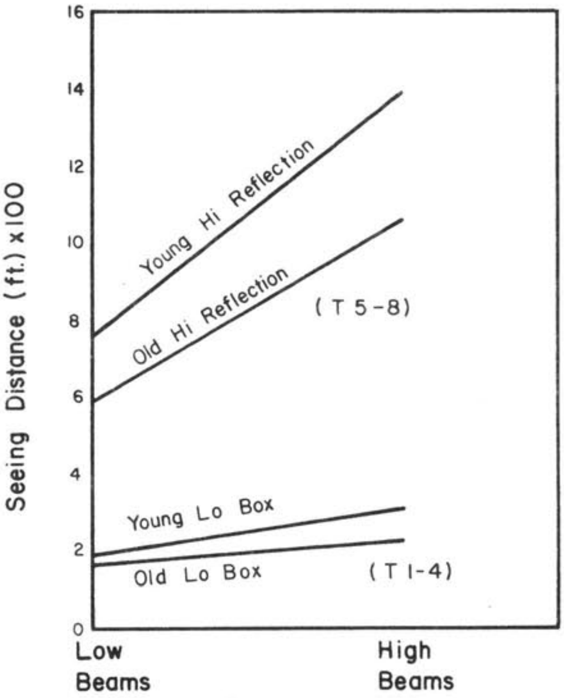

FIGURE 7. SEEING DISTANCE VS. BEAM CONFIGURATION, BY AGE GROUP AND TARGET TYPE

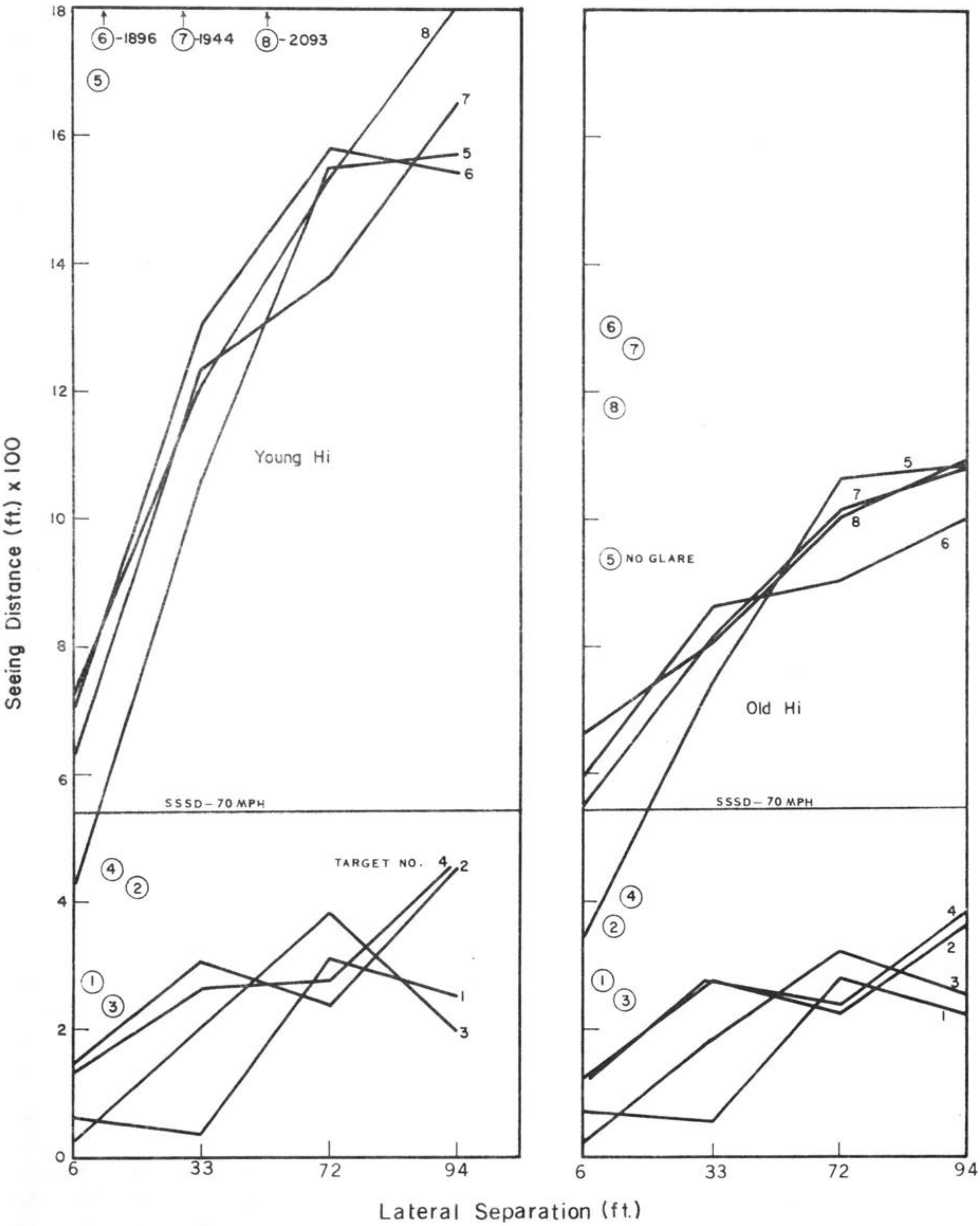

FIGURE 8. SEEING DISTANCE VS. LATERAL SEPARATION,

BY TARGET, AGE GROUP, AND BEAM CONFIGURATION

(Continued on next page)

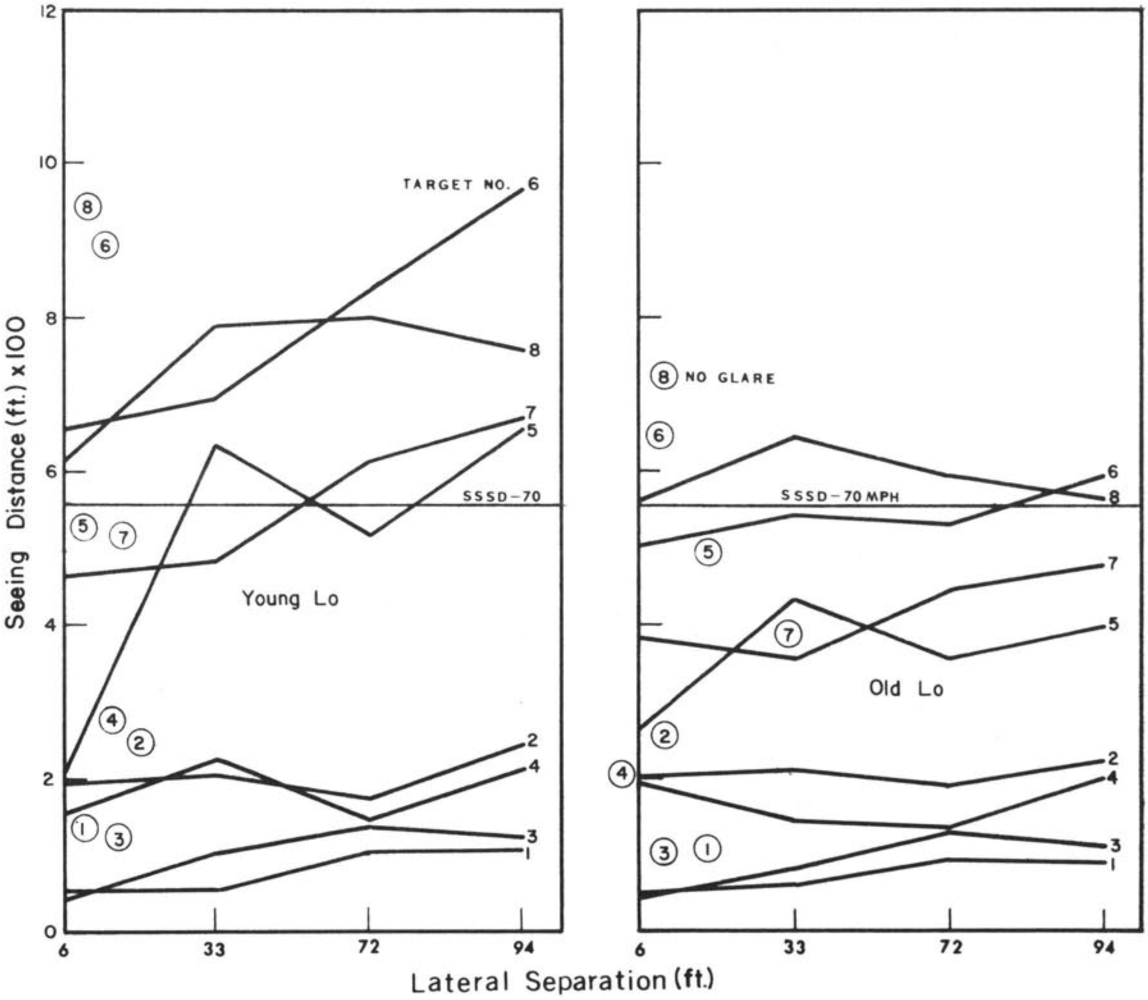

FIGURE 8. Continued

TABLE 5.

SAFE STOPPING SIGHT DISTANCES

Design Speed (mph)	Minimum Safe Stopping Sight Distances* (ft)
40	236
50	327
60	434
70	554

*For dry pavement, operating speed assumed equal to design speed.

Source: A Policy on Geometric Design of Rural Highways, A.A.S.H.O., Washington, D.C., 1965, p. 136.

combination. The horizontal line indicates the safe stopping sight distance at 70 mph on dry pavement. The no-glare condition (values indicated on graph by circle containing target number) was met by elimination of the oncoming glare source for high and low beams at 6-ft lateral separation. The mean minus one standard deviation seeing distance for each target is marked on the ordinate.

It can be seen from the figure that at no lateral separation were the low-reflectance targets visible at a distance that exceeded safe stopping sight distance for 70 mph. With low beams, little increase in seeing distance was evident across lateral separations, and comparison of this data with the no-glare condition indicated that seeing distance was at a maximum at the 94-ft lateral separation. To be able to see such low-reflectance targets at distances greater than the safe stopping sight distance required, an increase in lateral separation was of no value, and only an increase in the intensity of the observer's headlights would improve seeing distance. Data for the high-reflectance targets under low beam conditions was mixed, in terms of meeting the safe stopping sight distance criterion. For young subjects, targets 6 and 8 (located on the right side of the road at 300 and 600 ft behind the glare source, respectively) were visible even with 6-ft lateral separation. Targets 5 and 7 were not visible to the older subjects at any lateral separation under low-beam conditions.

With high beams, the seeing distance for the high-reflectance targets increased rapidly with an increase in lateral separation. Three of the four target placements were visible under 6-ft lateral separation conditions, and increases in lateral separation served only to provide extra protection in terms of added seeing distance.

D. POLARIZED HEADLIGHTING

Table 6 contains data on the effects of polarized headlighting for high beams at 6-ft lateral separation. Several conclusions are evident from this information. For both age groups, the seeing distances for the low-reflectance targets (nos. 1-4) were increased by polarizing the high beams at 6-ft lateral separation. This increase was also evident among the young age group for the high-reflectance targets (nos. 5-8), but for the old age group (except for target 5) seeing distances decreased slightly with polarized headlighting. In general, the polarization appeared to be more effective for younger subjects than for older ones.

For low-reflectance targets, an increase to 33-ft lateral separation provided nearly the same seeing distance as polarized headlighting at 6-ft lateral separation (except for target 1). This seeing distance was still far below the safe stopping sight distance required for 70 mph (556 ft), however. An increase to a 33-ft lateral separation provided substantial seeing distance increases (over polarized 6-ft lateral separation) for high-reflectance targets. Older subjects, in fact, were able to see farther than the safe stopping sight distance for targets 5 and 6 when tested at 33-ft lateral separation, but not at 6-ft lateral separation polarized. Data indicated therefore, that increases in lateral separation were more effective in providing increased seeing distance than polatization of headlights. (All of the results on polarized headlighting were conservative, because during the actual testing the experimenters noted that the windshield of the test vehicle was slightly depolarizing the light.)

TABLE 6.

COMPARISON OF SEEING DISTANCES* UNDER POLARIZED AND NO-GLARE CONDITIONS AT 6-FT LATERAL SEPARATION

Target No.	Young Age Group				Old Age Group			
	No Glare	6-ft Lat.Sep.	6-ft L.S. Polarized	33-ft Lat.Sep.	No Glare	6-ft Lat.Sep.	6-ft L.S. Polarized	33-ft Lat.Sep.
1	273	63	113	34	274	72	101	59
2	427	25	243	202	360	23	200	185
3	238	147	72	310	241	122	--**	276
4	450	133	263	263	409	127	177	271
5	1685	416	820	1069	936	350	416	750
6	1896	628	1008	1234	1299	552	514	814
7	1944	707	834	1305	1263	597	573	865
8	2093	720	939	1216	1173	667	574	810

*Mean minus one standard deviation -- distances to the nearest foot.

**Observed values highly variable, such that the standard deviation exceeded the mean.

IV. CONCLUSIONS

The conclusions presented in this chapter are based solely on the results of the disability glare field tests. These conclusions are presented in three parts including those related to the overall experimental design, target type and placement, and lateral separation (including polarized headlighting).

A. OVERALL EXPERIMENTAL DESIGN

Of the six parameters investigated by an analysis of variance, namely subject, lateral separation, beam configuration, target, direction, and age group, all were highly significant ($p < .01$) in the analysis except for direction which was not significant. All interactions, except those involving direction, were significant also, indicating the inter-relationship of many variables in the consideration of seeing distance.

The main effects, as determined by the analysis of variance, were:

(1) Younger subjects had significantly longer seeing distances than older subjects (regardless of target type, beam, or lateral separation).

(2) High beams provided significantly longer seeing distances than low beams.

(3) Seeing distance increased directly as a function of lateral separation.

(4) The eight different targets produced different seeing distances.

B. TARGET TYPE AND PLACEMENT

The targets employed in the study consisted of two types (high-reflectance and low-reflectance) and were placed at selected longitudinal and transverse distances with respect to the glare sources. Specific analyses designed to pinpoint the effects of these factors produced the following conclusions:

(1) Target reflectance provided the greatest effect on seeing distance -- more important in fact, than the distance from the glare source.

(2) The target placement factor consisted of at least two-subfactors, namely angle of light impingement on the eye and contrast with the background.

(3) The contrast factor in target placement was more important for the low-reflectance targets than for the high-reflectance targets.

(4) The right-left placement of the target (with respect to the driving lane) was more important for the high-reflectance targets than for low-reflectance targets.

C. LATERAL SEPARATION

In order to recommend a lateral separation that provides safe stopping sight distance in terms of disability glare, several criteria may be considered. Decisions must consider whether (1) recommendations should be made for use with high or low beams, (2) the recommended lateral separation should be safe for all types of targets and placement combinations, and (3) decisions should be based on both young and old drivers. Such decisions can best be evaluated in tabular form which includes all combinations of factors affecting the recommendation.

Table 7 lists the speed at which seeing distance, measured by the mean minus one standard deviation, exceeded safe stopping sight distance for dry pavement conditions. No lateral separation provided enough seeing distance for all targets. The low-reflectance targets had seeing distances which were limited not by glare from oncoming vehicles, but by the small percentage of light that was reflected. Greatest increase in seeing distance for the high-reflectance targets is afforded by a change from 6-ft lateral separation to 33-ft lateral separation. For both young and old subjects, and for high beams, all high-reflectance target placements were visible at sufficient distances when a 33-ft separation was used. If the criterion should include the use of low beams, the 94-ft separation shows continued improvement.

With respect to polarization of headlighting for high beams at 6-ft lateral separation, polarization appeared to be more effective for younger subjects than for older. Also, increases in lateral separation appeared to be more effective in increasing seeing distance than polarization of headlamps.

TABLE 7.

SPEED AT WHICH SEEING DISTANCE EXCEEDED

SAFE STOPPING SIGHT DISTANCE

Lateral Separation		6 ft		33 ft		72 ft		94 ft	
Age Group		Young	Old	Young	Old	Young	Old	Young	Old
Target	Beam								
1	Hi	--	--	--	--	40	40	40	--
	Lo	--	--	--	--	--	--	--	--
3	Hi	--	--	--	--	50	40	--	40
	Lo	--	--	--	--	--	--	--	--
2	Hi	--	--	40	40	40	--	50	50
	Lo	--	--	--	--	--	--	40	--
4	Hi	--	--	40	40	40	40	60	50
	Lo	--	--	--	--	--	--	--	--
5	Hi	50	50	70	70	70	70	70	70
	Lo	--	40	70	60	60	50	70	50
7	Hi	70	60	70	70	70	70	70	70
	Lo	60	50	60	50	70	60	70	60
6	Hi	70	70	70	70	70	70	70	70
	Lo	70	60	70	60	70	60	70	70
8	Hi	70	70	70	70	70	70	70	70
	Lo	70	70	70	70	70	70	70	70

*Seeing distance, measured by the mean minus one standard deviation of the observations made in field testing.

PART III
DISCOMFORT GLARE FIELD TESTS

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I. INTRODUCTION

The second phase of field testing concerned the problem of discomfort glare or glare from oncoming headlights which is physiologically and psychologically uncomfortable for the driver while not necessarily hindering the vision of objects. Part I of this report covered in detail the various factors which account for the amount and effects of glare, and it is necessary in this section only to relate previous studies of discomfort glare and to describe the generally accepted procedure for measuring discomfort glare, namely BCD (borderline between comfort and discomfort).

A. RELATED PAST STUDIES

It has been demonstrated, in References 13 and 154, and in Part II of this report, that the maximum seeing distance afforded in the night driving situation is provided by the use of high beams on both the observer's car and the oncoming car, for the entire passing maneuver and for all median widths. G. Johansson, et al.[154] compared the European high beams with both asymmetrical and symmetrical dipped headlights, and concluded that full (high) beams gave visible distances as great as or greater than dipped (low) beams for the whole course of the meeting. This relationship held for the different target reflectances tested, with the highest reflectance producing the greatest visible distance. It was also true that the high beams, as opposed to the asymmetrical dipped beam (which gives the same angle of beam on the left as the symmetrical dipped but a longer beam on the right side), provided greater seeing distance in a hill meeting situation.

S. Bergström[13] reported that full headlights on both vehicles gave greater seeing distances for all reflectances tested (6, 11, and 25 per cent, reflector tape), and concluded that if the only criterion of efficiency of meeting lights is visible distance, drivers should use high beams. He also noted that visible distances are all so short that they are exceeded by the braking distance at speeds greater than 15 to 25 mph. In conclusion S. Bergström stated that high beams are not good meeting lights, but they are better than low beams.

Neither of the two studies reported above attempted to evaluate the amount of glare present in the passing situation. V. J. Jehu and G. Hirst[153] reported that a median width of 130 ft negated all effects of glare. At a 10-ft median width, seeing distance was reduced to one-fourth that of the no-glare situation and at a 25-ft median width, it was reduced to one-half that of the no-glare situation. Beyond a lateral separation of 25 ft, seeing distance with high beams became progressively better, but discomfort glare was still present. The authors pointed out that the absolute values of seeing distance were the same with opposing high and low beams. Jehu and Hirst[153] gave no indication of how their evaluation of glare discomfort was obtained.

In a report by L. D. Powers and D. Solomon,(209) it was concluded that the discomfort effect was elusive of definition and measurement, resulting in highly variable between- and within-subject variance. Further tests by these authors centered on "what was thought to be the more critical problem of disabling glare."(209)

The question arises that if high beam vs. high beam provides the maximum seeing distance (G. Johansson, et al.;(154) S. Bergström(13)) and if it is assumed that disability glare is greatest in this situation for the median widths tested, and if the presence of disability glare does not shorten the absolute seeing distance of high vs. high beam to less than the low vs. low beam situation (Jehu and Hirst(153)), then what factors of this high vs. high beam situation cause researchers to exclaim, "A meeting situation with upper beam only ... is ghastly" (S. Bergström(13))? It must be assumed that the objection to such a solution to the night vision problem is based on psychological factors that are included in the term discomfort glare, and that this discomfort glare must be evaluated in order to determine the optimum lateral separation.

B. BCD AS AN EVALUATION OF DISCOMFORT GLARE

The borderline between comfort and discomfort (BCD) was first proposed by M. Luckiesh and S. K. Guth(181) as an attempt to quantify the quality of lighting that determines whether a source is comfortable or uncomfortable. Comfort and discomfort are sensations that vary considerably among indivisual observers. In the original study, 50 subjects reported the BCD as ranging from 315 fl to 1600 fl (geometric mean = 830 fl) with a field brightness of 10 ft. Luckiesh and Guth summarized the parameters involved in the sensation of discomfort glare:

(1) Brightness of the source
(2) Visual size of the source
(3) Surrounding brightness
(4) Position of source in the visual field
(5) Number of sources
(6) Configuration of sources

In discussing the discomfort glare problem, Putnam and Gilmore(213) remarked that:

> Visual comfort is based on certain physiological and psychological factors which vary greatly from one individual to another and even vary in a given individual from day to day. The only method for rating the comfort of a light source, therefore, is to have a large number of observers rate the sensation, not once but preferably many times.

Large groups of subjects and many repeated measures are necessary to determine the significance of absolute values of such a variable;(213) BCD's obtained from a limited number of subjects will generally establish the basic relationships necessary for evaluation of the lateral separation problem.

R. C. Putnam and R. E. Faucett(212) allowed subjects to make three adjustments of the brightness of the glare source. The first trial consisted of bracketing the BCD by varying the brightness to either side. For the second and third trials, subjects adjusted the brightness either up or down without overshooting or undershooting the BCD. R. C. Putnam and K. D. Bower(211) tested 14 observers, whose BCD's, while consistent within each person, ranged from 8 to 1420 fl with a geometric mean of 160 fl. The geometric mean was suggested for use due to the fact that it was less sensitive to extreme values then the arithmetic mean.

In summary, the need for study of the discomfort glare situation in highway driving is evident in light of the desirability of using high vs. high beams for maximum seeing distance. Most of the previous studies (References 97,105,211,212,213,217,223,286) dealing with discomfort, however, have concentrated on the problems of roadway lighting, indoor lighting, and on laboratory test situations. It was therefore the objective of this phase of the study to determine, for the driving situation, the relationships of discomfort glare to lateral separation.

● ●

II. RESEARCH PROCEDURE

The field testing of discomfort glare is described in the following sections which cover the experimental design, the test apparatus, the subject testing and description, and the test procedure.

A. EXPERIMENTAL DESIGN

The main design of the discomfort glare field tests consisted of two parts: static tests and dynamic tests. The static tests were conducted at eight longitudinal distances from the glare sources, four lateral separations, and two beam configurations, with measurements repeated five times for each of the ten subjects. The longitudinal distances considered were 200, 400, 800, 1200, 1600, 2400, 3200, and 4000 ft, and the lateral separations were 6, 33, 60, and 94 ft. For the dynamic tests, the four lateral separations and the two beam configurations were the test variables, with five repeated measures made under each condition by each of the ten subjects.

During the disability glare field tests (discussed in Part II of this report) a subjective rating of discomfort glare was obtained. The design resulted in data for two age groups, two beam configurations, all eight targets, and four lateral separations (6, 33, 72, and 94 ft).

B. TEST APPARATUS

The field tests were conducted during the late summer of 1966 on a completed but unopened section of Interstate 57 south of Mattoon, Illinois. The test section, shown in Figure 9, was a tangent portion of a four-lane divided highway. Two 12-ft portland cement concrete pavements (in each direction) were separated by a depressed (turf covered) 64-ft median. Ten-ft surface treatment shoulders flanked the outside of the lanes, with 4-ft wide inside shoulders.

The glare sources were identical to those employed in the disability tests. (See Figure 2.) The headlamps were aimed using a factory-calibrated Weaver Headlight Tester (Portable Model WX-45), as well as a set of mechanical headlight aimers (Hopkins Manufacturing Company, Kansas). As in the disability tests, the headlights were aimed according to SAE specification J579. The intensities of the headlights were set with the aid of the Weaver Tester and the proper intensity obtained by the use of an adjustable resistor in the power line to each headlight set. (See Table B in Appendix for headlight intensities.)

The glare sources were powered by a 12-volt DC gasoline generator. A control box which contained switches for high and low beams for each headlight set was wired between the generator and the frames.

As previously mentioned (Part III, Chapter 1, Section B) many parameters are associated with discomfort glare. It was the initial intent of the field test procedure to vary the brightness of the glare source (by means of a rheostat) to obtain the BCD.

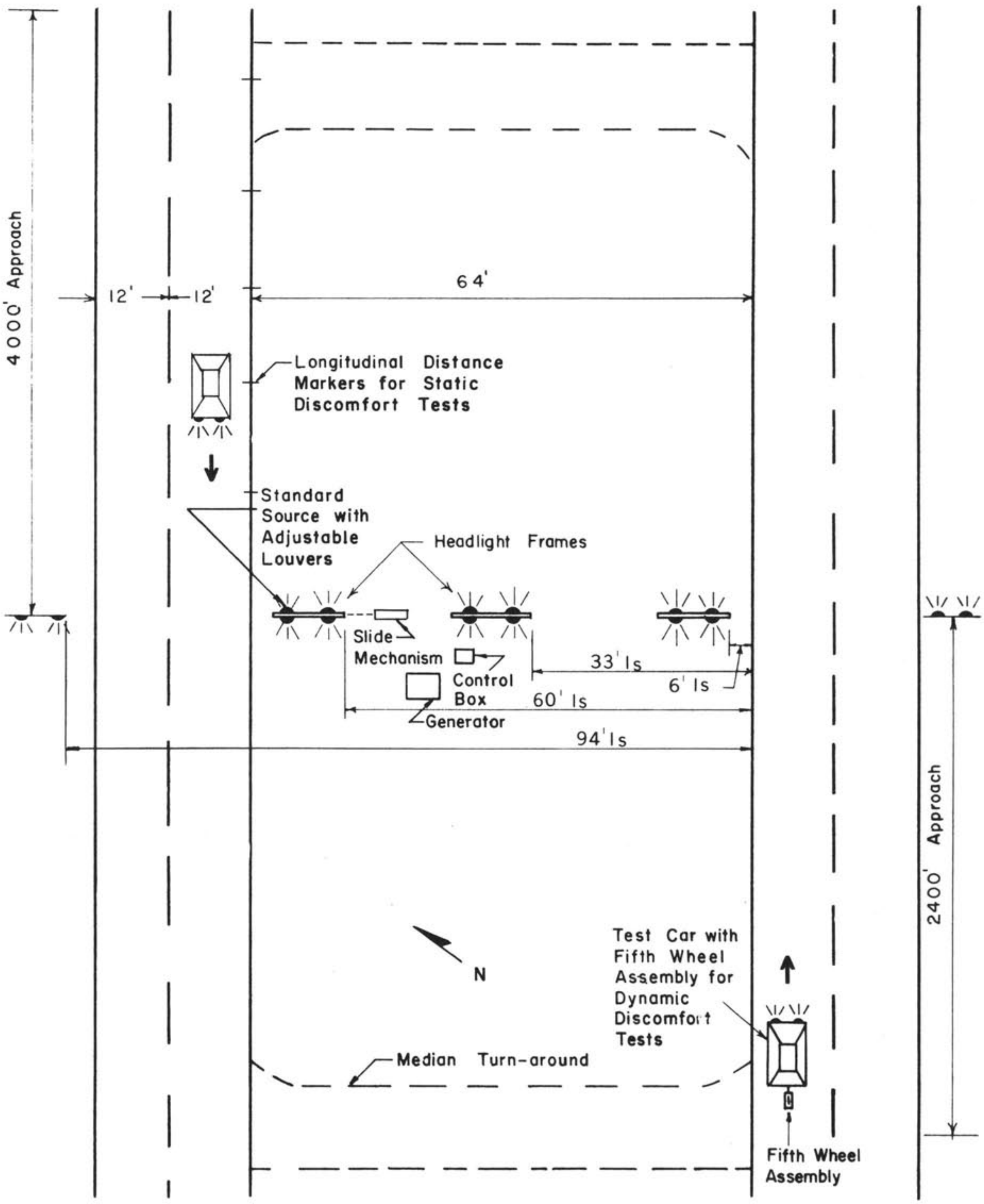

FIGURE 9. LAYOUT OF DISCOMFORT GLARE TEST SECTION

Unfortunately, technical difficulties arose mainly in that a color change occurred when the rheostat was employed and the application of neutral density filters to correct this problem was not feasible. A decision was then made to attain a variation of discomfort glare by varying the source size. The variables for the static test therefore were source size in addition to distance from the source (affecting the brightness of the source), lateral separation, and beam configuration.

A set of movable louvers was attached to one of the 6-ft lateral separation headlight frames. By moving a sliding mechanism on a control board (calibrated with a yardstick) one wooden louver would descend over the face of the headlamps and another would rise from below the headlamps, thus effectively reducing the size of the source. These louvers could be maneuvered slowly so as to produce a gradual increase in source size (and amount of discomfort glare) from a point when there was nearly no light to a point where the full size of a normal high-beam headlamp was present. At any given point, the mechanism could be held in a fixed position. The other piece of equipment was a headrest for the subjects (drivers). The vertical member of the headrest fastened to the car door by means of the window channels and was adjustable (front to rear) to accommodate individual differences. Attached to this vertical member was a horizontal member (adjustable up and down) which contained a plexiglas chin rest and two adjustable temple supports. The purpose of this headrest was to hold the subject's head steady and in the same position while he made the static discomfort judgments.

For the dynamic tests, distances were measured with a Performance Measurements Company Model PM-1625 Fifth-Wheel assembly attached to the rear bumper of a 1966 Ford four-door sedan. The accompanying decade counter was placed in the rear seat of the car.

C. SUBJECT TESTING AND DESCRIPTION

Four tests of visual ability were administered to each of the ten subjects prior to the field testing. These tests were performed with a T/O Vision Tester (Titmus Optical Company) and a Night Vision Meter and the results are shown in Table 8. Further discussion of the meaning of these measures and reasonable values of each was given in Part II, Chapter 1, Section D. For these test subjects, the median glare vision, night vision, and glare recovery were 27.1, 5.7, and 11.4, respectively.

In addition to the normal vision tests, the subjects underwent a pretest which was designed to provide some limited training in determining BCD values. Using the Night Vision Tester (modified with higher intensity light sources and a rheostat), each subject was instructed to indicate (orally) when the brightness reached his BCD level [note that the pretest varied brightness (fl), as opposed to the test procedures]. Several measures were taken (both with the brightness increasing to the BCD and with the brightness decreasing to the BCD) for each subject and the lack of a large variability in these judgment readings was used to indicate that the subject understood and could perform the task. The ranges and means (as a possible indication of the relative limits between subjects) are given in the last column of Table 8.

D. TEST PROCEDURE

The purpose of the following procedure was to determine the size of the 6-ft lateral

TABLE 8.

SUBJECT DESCRIPTION (DISCOMFORT GLARE TESTS)

Subject Number	Age	Glasses Worn? (for distance viewing)	Type	Snellen Equiv. For Vision (20 ft) (corrected vision)	Glare Vision*	Night Vision*	Glare Recovery Sec	Discomfort Glare Present	
								Range of BCD Settings	Average BCD Setting (6 trials)
1	31	No	--	20/20	43.3	11.0	7.7	27	43.0
2	21	No	--	20/25	18.0	7.3	8.0	N.U.**	--
3	24	No	--	20/18	39.7	3.7	14.0	9	62.3
4	26	No	--	20/13	37.3	5.7	12.7	15	26.7
5	21	No	--	20/25	40.0	11.7	12.7	10	48.5
6	25	No	--	20/15	12.7	2.3	4.7	18	22.3
7	23	No	--	20/25	16.7	3.7	7.0	11	33.2
8	22	Yes	Regular	20/13	27.0	7.3	10.0	14	26.0
9	32	Yes	Regular	20/22	27.1	5.3	15.0	11	24.8
10	23	Yes	Regular	20/13	22.3	5.7	14.3	18	49.5

*Average of 3 trials -- Night Vision Tester -- Rheostat Settings

**N.U. -- Not Uncomfortable

separation light source which produced BCD discomfort glare in order to compare sources at varying median widths to this size. BCD values were obtained at distances of 200, 400, 800, 1200, 1600, 2400, 3200, and 4000 ft from the glare source. After the subject signaled readiness from the proper distance, the experimenter adjusted the size of the standard source by moving the set of louvers into the path of the headlights on the 6-ft lateral separation frame. Each subject indicated his BCD for an increasing and a decreasing source size. The average was taken and this value was used as the subject's BCD at that distance.

For the static test, so named because the subject's position was stationary at the time of observation, the test source 6-ft lateral separation, from northeast direction (see Figure 9), was presented at the BCD for that distance for two seconds. The test source was then turned off and the subject was presented with full-size sources, in a random series, from any of four lateral separations (6, 33, 60, 94 ft) and two beam configurations (high or low). This comparison source was presented for two seconds and following its extinction, the subject was asked to rate the discomfort glare of the second (comparison) source in relation to that of the first (standard, set at BCD) source, on a numerical scale. A value of ten was to be assigned if the comparison was equal in glare value to the standard. If the comparison source was more or less uncomfortable than the standard source, numbers proportional to this difference were to be reported. This procedure was repeated at all eight distances (presented in a limited random order) five times for each of the ten subjects.

In the dynamic testing, subjects were instructed to accelerate and maintain approximately 60 mph and, at the point at which the glare from the opposing vehicle's lights became uncomfortable (BCD), to indicate this to the experimenter in the car. The experimenter then activated a decade counter attached to the fifth wheel to measure the distance from the point of BCD to the glare source. Observations were made on a closed circular track (Figure 9); lateral separation and beam configuration were randomly presented and each subject made five observations of each treatment combination, two from one direction and three from the other. Photometric values of the output of the glare sources were determined at the end of testing. This procedure differed from the original intent of the design. Originally the Pritchard photometer and integrating glare lens were to be used to record a continuous intensity of the glare source as a function of distance from the glare source. However, highly fluctuating values were obtained as the car moved due in part to: the critical aiming features of the glare lens; a technical problem with the pen recorder; and the power output from the car battery and DC to AC inverter. The nature of the integration performed by the lens (see Reference 87) may also have caused some instability. Consequently no intensity measurements were made at the time of testing for each subject.

In conjunction with the disability glare tests discussed in Part II of this report, subjective discomfort measures were secured. After each observation (passage by the headlight frame) the driver was asked to rate the discomfort of the headlights on a 1 to 5 scale. The meanings of these ratings were as follows: 1 = no discomfort glare; 2 = little discomfort glare; 3 = come discomfort glare; 4 = much discomfort glare; and 5 = subject blinded by glare. It should be emphasized that these judgments were made under the dynamic driving situation at 45 mph.

III. STUDY RESULTS

The results of the discomfort field tests are presented in the sections which follow, covering the static test, the dynamic test, and the subjective discomfort ratings obtained during the disability testing.

A. STATIC DISCOMFORT TEST

Due to the need or desirability to maintain high vs. high-beam conditions for maximum seeing distance, the majority of the results of the static discomfort test deal with the high-beam condition. It should be noted, however, that test results indicated that with low beams, all treatment combinations were reported as presenting glare at lower-than-BCD values.

BCD measurements showed a large between-subject variability similar to that reported by M. Luckiesh and S. K. Guth,(181) R. C. Putnam and W. F. Gillmore,(213) R. C. Putnam and R. E. Faucett,(212) and R. C. Putnam and K. D. Bower.(211) There was also a wide range of distances at which a BCD was reported. Four subjects reported BCD's out to the maximum distance tested (4000 ft); for one subject, only at 200 and 400 ft was the size setting so large as to produce the sensation of a BCD. The measurements taken concerning BCD size are only proportional to size and do not measure size in terms of area. The method of varying the size of the light source (Chapter II, Section B of Part III) precluded exact area measurements of the stimulus.

(As previously mentioned, the following paragraphs deal only with the high-beam situation.)

Functions for each of the four lateral separations were fitted by eye to the median response of ten subjects for each treatment combination in the comparison to BCD test. Functions were not extended past 3200 ft because only three of the ten subjects reported a BCD at 4000 ft. Figure 10 indicates these functions.

Past 1600 ft, little difference can be seen between the discomfort glare ratings for the four lateral separations tested. Extrapolation past 1600 ft is unreliable due to the decreased number of subjects making judgments at these distances. Data points are biased to the extent that subjects to whom the maximum intensity at that distance was not uncomfortable are not included. The bias is inherent in the experimental design which allowed those subjects to whom the output was uncomfortable (low BCD, low tolerance to glare) to respond, while it eliminated from response at longer distances those subjects with a high tolerance to glare.

Figure 11 is the frequency distribution of subjects reporting a glare value above BCD for each distance-median combination. A subject's response was taken as the mean of the five observations, and these averages were dichotomized as "above BCD" and "at or below BCD." All ten subjects reported that the

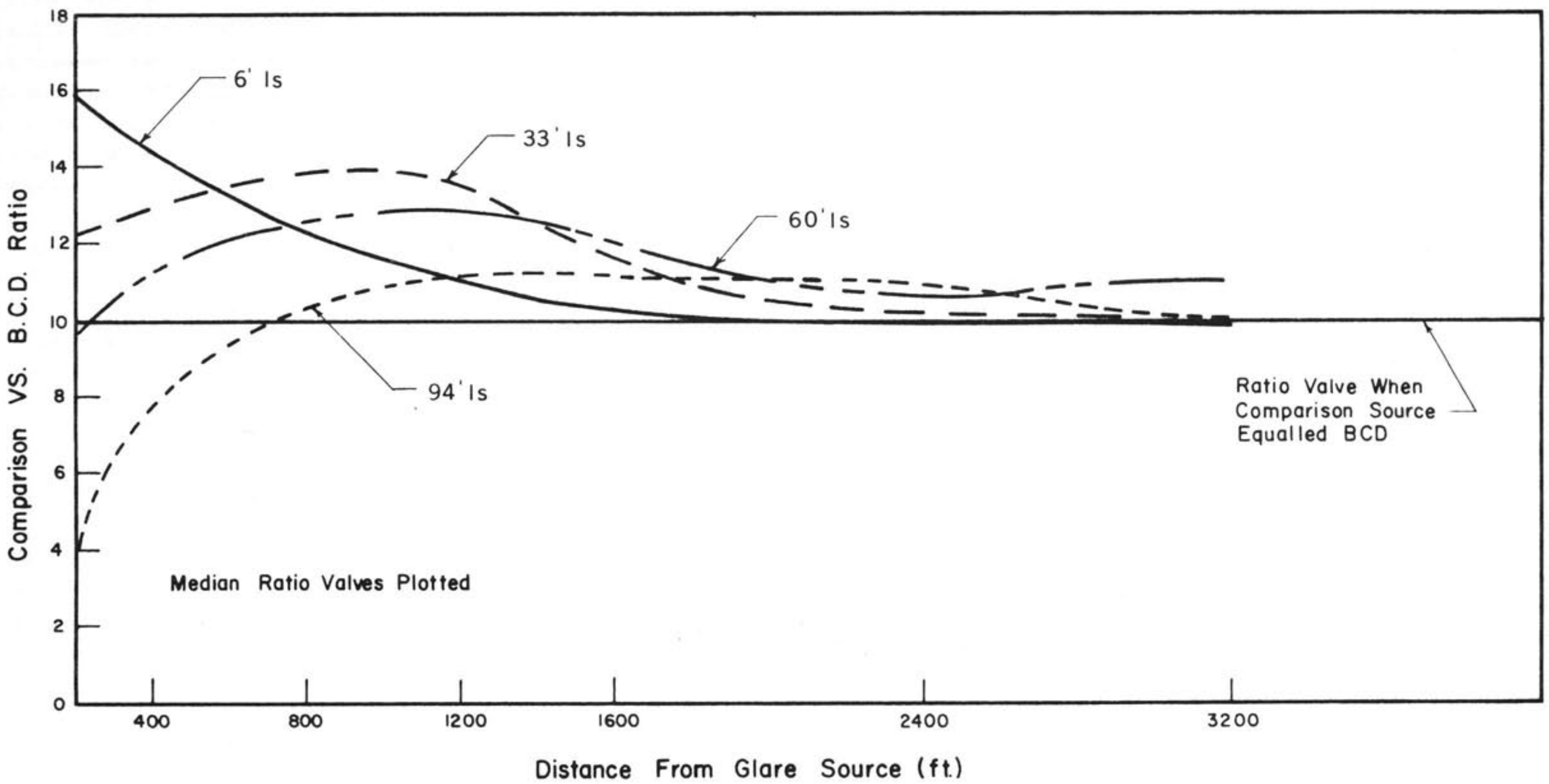

FIGURE 10. COMPARISON SOURCE VS. STANDARD (BCD) SOURCE, BY LONGITUDINAL DISTANCE

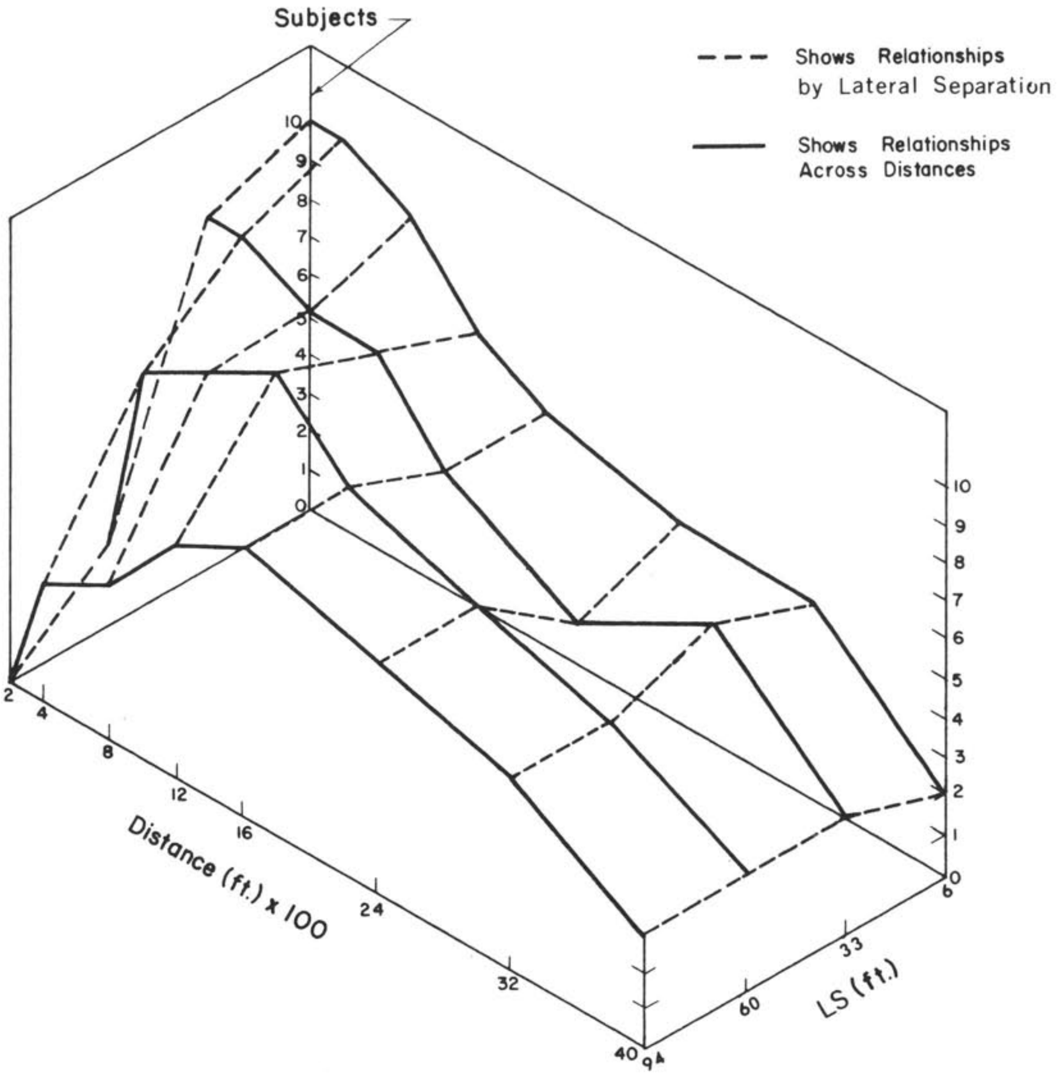

FIGURE 11. FREQUENCY DISTRIBUTION OF SUBJECTS REPORTING DISCOMFORT GLARE

6-ft lateral separation at 200 and 400 ft provided an uncomfortable amount of glare. This figure, as opposed to Figure 10, takes into account those subjects who reported no BCD at longer distances and gives information about the degree of discomfort in terms of the number of subjects reporting such discomfort. The interaction of lateral separation and distance from glare source which produced discomfort glare can be seen here. The distance at which maximum discomfort glare was produced depended on the lateral separation chosen.

B. DYNAMIC DISCOMFORT TEST

A maximum brightness function for each beam, lateral separation, and direction was determined after all dynamic data were collected. Functions from the two directions for a given lateral separation and beam configuration yielded markedly different values, indicating the possibility of (1) different stimulus output or (2) variable photometric measurements, or both. Extrapolation of distance measures to obtain BCD brightness values was highly questionable in light of variance of maximum brightness functions.

Results of the dynamic discomfort test are biased in the same manner as the static test; the experimental procedure allowed selective responding between subjects and numerical results reflect BCD distances and brightness of only those subjects who experienced the sensation of discomfort glare. Those subjects who reported no glare are not represented in the data and therefore, BCD brightness values are biased upward as lateral separation increases. At a lateral separation of 94 ft, only five of the nine subjects* reported a BCD.

*One subject's data were unavailable due to faulty equipment.

The distance at which BCD was reached was highly variable, due in part to natural between-subject variation, and probably increased by the method of distance measurement. Results indicated generally that BCD distance decreased as lateral separation increased, which was predicted on the basis of maximum brightness curves. Results are tabulated in Table C in the Appendix.

The relation of the dynamic results to the static results is not clear. More meaningful results, in terms of amount of discomfort glare, are available from the static test.

C. SUBJECTIVE DISCOMFORT RATINGS FROM DISABILITY TEST

As previously stated, in addition to the distance measures collected for the disability glare tests (see Part II of this report), subjects were asked to scale the brightness of the glare source on a five-point scale, from "no discomfort" to "blinding glare."

For the young subjects, the shape of this function (Figure 12) shifted as the median width was increased. At 6-ft lateral separation, high beams, the curve peaked at 5, indicating the highest level of reported glare. When the lateral separation was increased to 94 ft, the majority of responses indicated no glare or a small amount of discomfort present. This trend continued with the use of low beams. Some overlap in efficiency of reducing discomfort glare was indicated by the similarity of the 94-ft lateral separation, high beam, and the 6-ft and 33-ft low-beam functions. As would be expected, the 94-ft low-beam condition effectively eliminated discomfort glare.

Responses of the older subjects differed in a systematic manner from the younger subjects. Only the 6-ft lateral separation, high-beam condition elicited responses of "blinding

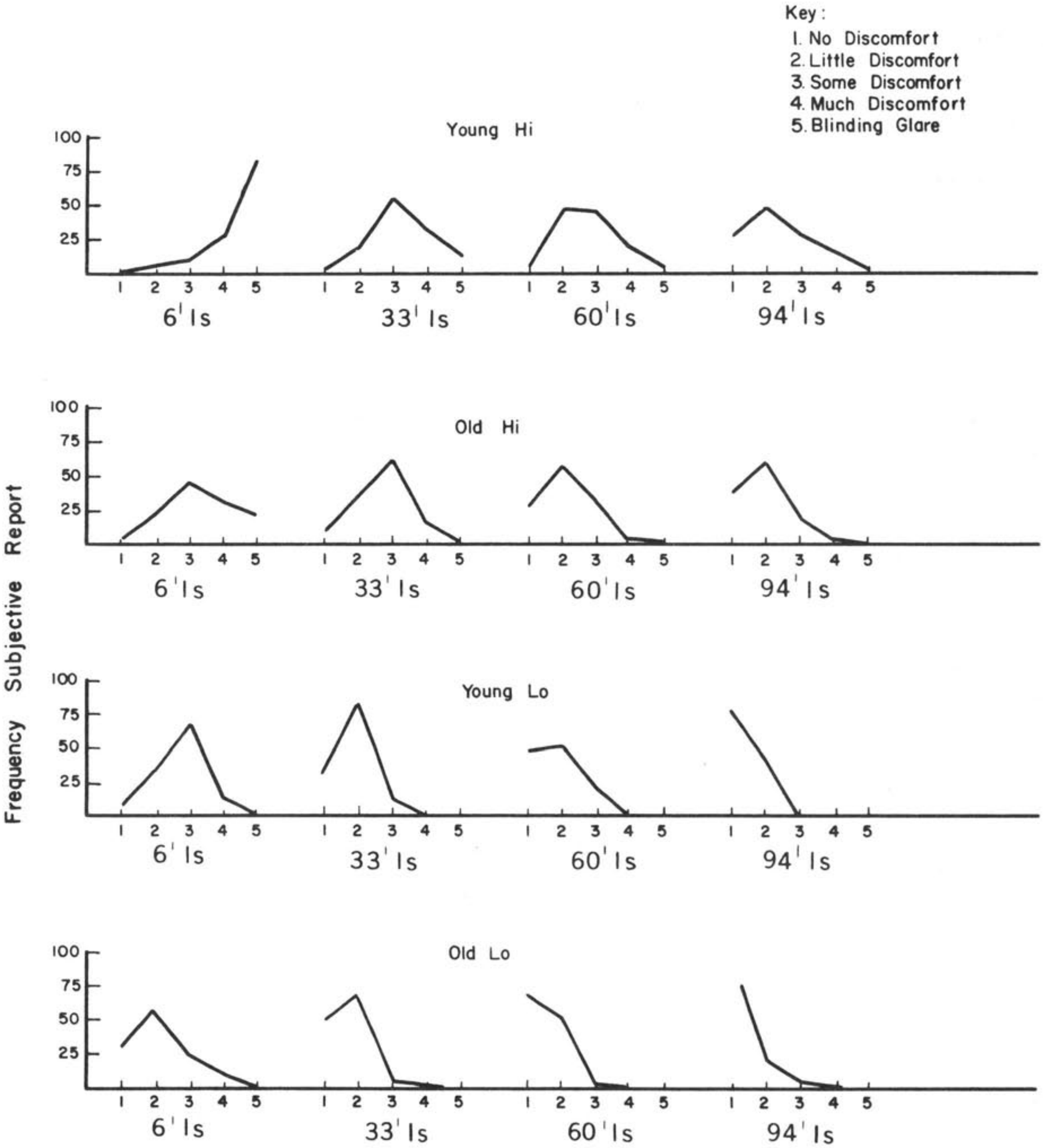

FIGURE 12. SUBJECT DISCOMFORT RATING FREQUENCY DISTRIBUTIONS

glare;" the majority of responses indicated only a moderate amount of glare in the situation that was called blinding by the younger subjects.

This difference in discomfort glare as a function of age seems to be the reverse of what would be expected, namely that since older subjects are deficient in all other visual abilities (see Part I, Chapter III) they would report more discomfort glare. Explanation of this reversal may be in terms of the learning factors suggested to account for the shifting BCD: that older drivers, having more experience in the driving situation, have developed more tolerance to glare. This result contradicts data by C. H. Rex and J. S. Franklin[223] which indicated no correlation between BCD and age. It was on the basis of the Rex and Franklin data that age was not included as a variable in the discomfort test for this study.

Using the discomfort glare ratings from the disability study, the amount of discomfort glare present when the observer's headlights and the glare sources were polarized was determined. Subjects reported glare on a 5-point scale with 1 = no discomfort and 5 = blinding glare.

As would be expected, discomfort glare was independent of the target type. Between-subject differences were evident as each subject made all judgments on a small range of the scale. Of the 240 observations, 64 per cent reported no glare, and approximately 30 per cent reported little or some glare. Polarized lighting was therefore very effective in reducing sensations of discomfort glare. (See Figure 12 for comparison.)

IV. CONCLUSIONS

The conclusions presented in the following sections are based solely on the discomfort glare field test results (with the exception of the subjective rating results collected from the disability glare field tests). Results are presented in sections dealing with static tests, dynamic tests, and desirable lateral separations.

A. STATIC TEST

With the static discomfort test, the BCD (borderline between comfort and discomfort) measurements showed a large between-subject variability as had been expected from previous studies. Static tests which involved comparing headlight sources at various lateral separations to the BCD source indicated that for all treatment conditions (eight longitudinal distances, two beam configurations, and four lateral separations) the low beams provided less-than-BCD values, meaning that low beams at all lateral separations were deemed comfortable by the ten test subjects.

Analysis then concentrated on high beams and found that past 1600 ft from the glare source, little difference was evident between the glare ratings of the four lateral separations. At closer distances the ratings varied widely.

Further analysis also indicated that at 200 and 400 ft all ten subjects reported the 6-ft lateral separation high beam to be uncomfortable. The distance at which the maximum discomfort glare occurred for other lateral separations varied from 400 to 1600 ft depending on the lateral separation.

B. DYNAMIC TEST

Due to difficulties in the test procedure, the data from the dynamic test results gathered in the summer of 1966 were ambiguous. The points at which BCD brightnesses were reached were generally at a distance prior to differentiation of the maximum brightness curves for the four lateral separations. The dynamic test was not exactly comparable to the static test because the latter involved manipulations of source size as well as source brightness.

The discomfort ratings obtained during the dynamic disability glare test did produce meaningful results. Young subjects (20 to 30 years old) indicated a decreasing discomfort as the lateral separation increased. At 94-ft lateral separation the majority of subjects indicated no discomfort or only a small amount present. Older subjects (50 to 60 years) gave a "blinding glare" response to only one condition (6-ft lateral separation, high beams). The majority of responses indicated only a moderate amount of glare where younger subjects considered it objectionable. It is possible that an experience or learning factor influenced older subjects to accept higher glare intensities more readily.

C. DESIRABLE LATERAL SEPARATION

At distances close to the glare source, the greatest improvement in the amount of discomfort glare was gained by the use of the 60-ft lateral separation. However, no lateral separation provided all the subjects with comfortable amounts of glare at all distances. Even with the 94-ft lateral separation, seven out of ten subjects reported uncomfortable glare at 1600 ft. These data are for high beams, which were considered necessary in terms of providing the needed seeing distance. With low beams, as previously mentioned, all conditions were reported as having comfortable glare levels.

PART IV
A SUMMARIZATION OF THE HEADLIGHT GLARE PROJECT

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I. INTRODUCTION

In order to receive the maximum social and economic value from the multi-billion-dollar investment in streets and highways, it is imperative that every aspect of design be considered in terms of safe, comfortable, and convenient movement of people and goods. This obviously requires provision of the designed level of service during the night as well as daylight hours. However, the higher night accident rates indicate that our present system is not providing this same level of service.

The primary inequity between these two times of day is the difference in the level of illumination available to the motor vehicle operator, with other factors such as driver fatigue and inattention also contributing. The low illumination level at night reduces the driver's visual ability and any factor, such as headlight glare, which further reduces his visibility and/or comfort can be considered a highway safety hazard.

Headlight glare, as has been previously mentioned, is divided into two categories. The first, physiological or disability glare, causes a measurable modification in the visual functions of the driver and results in a decreased seeing distance.[(116)] The second, psychological or discomfort glare is glare which causes discomfort while not necessarily hindering the vision of objects appearing in the visual field.[(286)] Therefore, disability glare is primarily responsible for impairing the ability to perform a visual task, while discomfort glare influences the ease with which the individual can see.[(101)]

Several means of reducing headlight glare are available, and include the following:

(1) Tinted windshields, glasses, and contact lenses. These media have been found to reduce the transmission of light (and thereby shorten seeing distance) while not significantly reducing headlight glare.

(2) Polarized headlighting. This method maintains seeing distances comparable to current high beam systems while reducing glare to a fraction of that of low beams. Problems have arisen primarily in the transition to this new system.

(3) Street lighting. Street lighting increases background illumination and thus reduces glare. The main drawback is the enormous cost of installation and maintenance.

(4) Median design. There are two aspects of median design with regard to headlight glare. The first is barriers in the median which are designed to block opposing headlights but these devices have proven partially ineffective and quite costly. Second, the amount of glare decreases with increases in the angle between the driver's line of sight and the glare source. Obviously, then, the lateral separation of vehicles associated with median design is a deterrent to headlight glare.

A. SUMMARY OF PROJECT WORK

It was the objective of the Headlight Glare Project (IHR-87, initiated in 1964) to determine the tolerable levels of headlight glare as related to median performance, thus concentrating on method (4) above as the possible means of reducing headlight glare. The initial step was the investigation of all previous research in the field and the preparation of an annotated bibliography on headlight glare.* From this bibliograpy, a report of the current status of knowledge on headlight glare (amount of, effects of, ways of reducing, etc.) was prepared. (Part I of this report)

On the basis of information gained in these first two steps, the project staff chose to divide the field tests into two segments -- one dealing with disability glare and the other with discomfort glare. It was further determined that for disability glare testing, the definition of a "tolerable level of headlight glare" was the point at which the seeing distance under the glare condition was equal to or greater than the total safe stopping sight distance. This tolerable level was then to be determined in relation to lateral separation (which is provided through the width of the median selected).

The details of the disability and discomfort glare field tests, conducted in the summers of 1965 and 1966, are discussed in Parts II and III of this report. It was the objective of the disability glare tests to replicate previous findings and to extend the scope by including factors not considered in previous studies. The objective of the discomfort glare tests was to extend the scope of previous static test studies to the dynamic conditions existing in current night driving practice. Both of these objectives were justified on the basis of the limited information currently available and the necessity for knowing more about the headlight glare problem in light of the growing mileage of divided highways. Finally, by combining tolerable lateral separation criteria from both the disability and discomfort glare approach, the optimal lateral separation could be determined.

It should be emphasized at this point again that the provision of adequate lateral separation (to reduce disability and discomfort glare) through median design is only <u>one</u> solution to the glare problem. Other solutions, it is remembered, include polarized headlighting, median barriers, and highway lighting. It must also be mentioned that reduction of headlight glare is only <u>one</u> function of median design and only one criterion for median width selection. Median widths must also be chosen on the basis of providing sufficient width (or barrier): to reduce or eliminate median crossings (and head-on collisions); to provide adequate room for maintenance; and to provide for adequate drainage facilities. Therefore, the results summarized in the section to follow are based solely on the consideration of lateral separation as related to disability and discomfort glare and based solely on the interpretation of data gathered during the field tests conducted by the project staff (as described in Parts II and III of this report).

B. CONCLUSIONS REGARDING GLARE AND LATERAL SEPARATION

Specific conclusions relating to the separate tests of disability and discomfort glare are given in the final chapters of Parts II and III of this report and they will not be repeated here.

*"Annotated Bibliography on Headlight Glare," IHR-87 Headlight Glare Project Report, University of Illinois, October, 1966, revised February, 1967, to be published by the Highway Research Board, early 1968.

The concern at this point is the selection of the optimum lateral separation for which the headlight glare of opposing vehicles is at or below the tolerable level in terms of disability and discomfort glare. For the purpose of providing a seeing distance greater than the safe stopping sight distance for the largest number of targets and both age groups, the disability test results indicated the necessity of considering high beam meeting conditions. In terms, then, of the high-beam situation (and particularly the high reflectance targets) a lateral separation of 33 ft or more provided adequate seeing distance for the 70-mph design speeds of current limited-access divided highways. However, at this optimum lateral separation with regard to seeing distance, the subjects in the discomfort glare tests reported an uncomfortable amount of glare. To provide comfortable levels of glare for the largest number of subjects, the 94-ft lateral separation was required.

It is therefore concluded that of the lateral separations tested, the 94-ft lateral separation provided the most tolerable levels of disability and discomfort glare for the high-beam meeting situations.

Low beams provided comfortable seeing under all conditions but restricted the seeing distances such that none of the low-reflectance targets were visible at a distance exceeding the safe stopping sight distance (for speeds greater than 40 mph). In order to see the high-reflectance targets in time to stop would require speeds to be limited to 40 mph with 6-ft lateral separation and 50 mph for the other three lateral separations.

Although increases in lateral separation appeared more effective in reducing disability glare than polarized headlighting, the value of polarized headlighting for the 6-ft lateral separation (equivalent to the two-lane, two-way highways) cannot be ignored. In most cases, polarization of current high-beam headlamps provided increased seeing distance. (See Table 6.) Furthermore, 64 per cent of 240 observations indicated no glare discomfort and 30 per cent indicated little or some discomfort with polarized high beams at 6-ft lateral separations. The effectiveness of polarization in terms of disability and discomfort glare is evident.

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II. CRITIQUE OF RESEARCH STUDY AND RECOMMENDATIONS

A. CRITIQUE OF THE STUDY

Several shortcomings were evident in the study procedure. These are described below along with suggestions for correcting these problems.

(1) The use of the circular track, providing two sets of glare sources, may have saved some time in data collection, but the introduction of this large source of error (unequal stimulus output from corresponding sources; see Table B) into the already variable between-subject data of the dynamic discomfort glare test served only as a confounding factor. Inadequate regulation of the output of the light sources may have contributed variance to the results. The static discomfort test, which collected data using only one direction, was free of this problem. Also, the disability data indicated that direction was not a factor in determining the seeing distances for the various targets.

(2) The photometer used in the discomfort glare study was inadequate for measuring the dependent variable, source brightness. The glare lens was designed to measure disability glare according to G. A. Fry's equation (see Reference 75) and its unique weighting system made it inapplicable to the measurement of discomfort.* The aiming of the photometer and glare lens was highly critical and slight misaiming resulted in a large variance in measures. Also, due to changes in headlamp intensity with time and the effects of atmospheric conditions, careful photometer readings should be made for every night of testing.

(3) The nature of the discomfort glare experimental design introduced bias into the results due to the selective responding at longer distances. Tolerance to glare and the BCD is known to be variable between subjects. When subjects did not report a BCD at some distance, no further comparisons to BCD were made at that distance (static test). Final results included only those subjects with relatively low tolerance or low BCD and therefore reports of comparison to BCD were elevated due to differential dropout of subjects.

The same bias was introduced into the dynamic test. Some subjects reported no BCD for some beam-lateral separation combinations, and the remaining data did not take this into account. This bias may be handled in either of two ways:

(a) Do not determine BCD for each distance from glare source. If the subject has the concept of BCD in mind, he may be able to judge discomfort glare in a magnitude estimation procedure without making a visual comparison on every trial. It may be that this procedure would be more variable, but it would eliminate the bias present in the original design. For long distances where BCD's were not reported, the subject would respond with some value in proportion to his concept of BCD.

*Discomfort glare is believed to have its physiological origin in the muscular contraction of the pupil (see J. M. Fugate and G. A. Fry, Reference 86) while most recent work on disability glare has focused on stray light within the eye (G. A. Fry, Reference 75).

(b) If it was felt that it was necessary to include a visual comparison to BCD on every judgment, the results may be kept unbiased by using a frequency count to determine magnitude of glare. Using this frequency count, the subject would only have to report the presence or absence of glare for any particular treatment combination. For the combination where no comparison value of BCD was reported, the experimenter would record "absence of glare."

(4) The method of measuring BCD distance in the dynamic discomfort test allowed reaction time of both subject and experimenter to introduce variance into the measures. To minimize this error, the subject should respond by activating the counter himself by pushing horn ring or a button of the floor.

Despite these shortcomings, the Headlight Glare Project produced some valuable output. The annotated bibliography prepared by the project staff provides an up-to-date source of references on this important topic of headlight glare. The summarization of past work (Part I of this report) is a brief "textbook" on the subject which is of value to anyone who wishes to familiarize themself with the current status of knowledge.

By employing a multi-factor approach, the disability glare field tests combined the work of previous studies and also added new information on some of the many interactions associated with the glare problem.

The discomfort glare tests were one of the first to ever attack the problem, under the driving situation, with headlighting (other work has been done in laboratories or with regard to street lighting). As might be expected when venturing into new frontiers, many problems arose, but the groundwork was laid and there is evidence that additional work along these lines will prove fruitful.

B. RECOMMENDATIONS FOR FURTHER STUDY

The problem of headlight glare is a highly complex one, but one which deserves continued attention in light of the increasing automobile population and expanding highway mileage. The problem of disability glare has been studied by many and the influence of beam configuration, driver age, target type, and lateral separation on seeing distance appear to have been well defined. The one area which may merit further attention is polarized headlighting and how it can be initiated, for its advantages in increasing seeing distance and reducing discomfort glare for two-lane highways are evident.

The phase of headlight glare requiring much additional study is discomfort glare. Studies of this phenomenon in actual driving situations have been few. It is important to realize, however, that this type of glare is based significantly on the human element in the driving situation and measurement of the amount of discomfort is difficult (especially in relation to disability glare, whose effects are more readily measured in terms of seeing distance). Psychologists, physiologists, and illumination engineers should be encouraged to delve into these problems to an increasing degree. ● ●

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REFERENCES

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REFERENCES

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APPENDIX

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TABLE A

INTENSITY OF GLARE SOURCES FOR DISABILITY GLARE TESTS

(Candlepower)

Frame No.	Beam Condition	Left Pair of Headlights: Type 2 Lamp	Left Pair of Headlights: Type 1 Lamp	Right Pair of Headlights: Type 1 Lamp	Right Pair of Headlights: Type 2 Lamp
1	H	10,000	23,000	28,500	15,000
	L	28,500			33,000
2	H	17,000	24,500	22,000	13,000
	L	25,000			39,000
3	H	12,000	24,000	23,000	18,000
	L	30,000			29,000
4	H	15,000	26,000	26,000	13,500
	L	31,000			31,500
5	H	13,500	20,000	25,000	14,000
	L	26,500			23,500
6	H	15,000	20,000	22,500	15,000
	L	29,000			27,500
7	H	13,500	25,000	24,000	12,000
	L	22,000			26,500
8	H	12,000	21,000	30,000	13,500
	L	28,500			32,000

KEY:

Frame No.	Lateral Separation
1, 2	6'
3, 4	33'
5, 6	72'
7, 8	94'

TABLE B

INTENSITIY OF GLARE SOURCES FOR DISCOMFORT GLARE TESTS

(Candlepower)

		Left Pair of Headlights		Right Pair of Headlights	
Frame No.	Beam Condition	Type 2 Lamp	Type 1 Lamp	Type 1 Lamp	Type 2 Lamp
1	H	12,500	23,000	21,000	11,000
	L	25,500			27,000
2	H	12,500	22,000	23,000	12,000
	L	30,000			31,000
3	H	14,500	27,000	23,000	15,000
	L	30,000			31,500
4	H	12,000	23,000	23,500	15,000
	L	29,000			32,000
5	H	13,000	22,500	22,500	12,000
	L	32,000			30,000
6	H	12,000	23,000	23,000	12,000
	L	23,000			33,500
7	H	13,500	22,000	23,000	19,000
	L	23,500			31,000
8	H	13,500	23,500	22,500	12,500
	L	31,000			25,500

KEY:

Frame No.	Lateral Separation
1, 2	6'
3, 4	33'
5, 6	60'
7, 8	94'

TABLE C

DYNAMIC DISCOMFORT TEST RESULTS

Subjects	Directions	Lateral Separations							
		6 ft		33 ft		60 ft		94 ft	
		Hi	Lo	Hi	Lo	Hi	Lo	Hi	Lo
1	NE	1036*	77	895	--	1414	--	--	--
	SW	1147	--	1223	--	582	--	--	--
2	NE	2207	833	3029	622	2357	514	1885	513
	SW	2375	1068	1884	546	1946	--	1640	--
4	NE	2845	397	1822	1108	2864	902	3561	1047
	SW	1792	1260	1899	458	1658	--	1695	--
5	NE	1076	--	1042	--	--	--	--	--
	SW	1222	--	1402	--	--	--	--	--
6	NE	1683	--	1270	--	936	--	--	--
	SW	1380	--	1292	--	732	--	--	--
7	NE	1329	122	1015	272	831	418	523	--
	SW	1105	685	1183	160	999	--	676	--
8	NE	3896	1983	3563	1056	3392	2451	3199	986
	SW	2550	2106	2044	1119	1793	435	1674	--
9	NE	1011	--	1005	--	728	--	--	--
	SW	1787	--	1005	--	--	--	--	--
10	NE	862	197	946	334	784	261	864	
	SW	1027	249	1070	266	1136	--	986	--

*Average in feet from glare source of 3 observations

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